

# **Fluvial Geomorphology Assessment of Northern Connecticut River Tributaries**

## **Final Report**



Upper Ammonoosuc River in Stark, NH

*Prepared for*

Connecticut River Joint Commissions  
Charlestown, New Hampshire

*Prepared by*

Field Geology Services  
Farmington, ME

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## **EXECUTIVE SUMMARY**

A fluvial geomorphic assessment of the Mohawk and Upper Ammonoosuc Rivers, tributaries to the Connecticut River in New Hampshire, has identified the major natural and human factors controlling sediment delivery to the Connecticut River mainstem where bank erosion threatens the Colebrook Business Park (adjacent to the Mohawk River) and Northumberland Cemetery (adjacent to the Upper Ammonoosuc). The Mohawk River is constrained by bedrock and glacial outwash terraces along much of its length, but several human factors have increased the river's sediment transport capacity above natural levels. Rock riprap is found along 13 percent of the river's banks, particularly through Colebrook, NH where the river is confined between concrete walls. In addition, over 50 percent of the channel's length has been artificially straightened with the lowest 0.5 miles straightened in the 1960's. The excess sediment transported to the mainstem as a result of these natural and artificial constraints has led to the deposition of large gravel bars at and downstream of the Mohawk River confluence; flow deflection around the bars is, in turn, causing severe bank erosion at the Colebrook Business Park. While the straightened channel segments remain relatively unchanged during low to moderate discharges, a dam break flood in 1929 resulted in multiple "break outs" where debris blocked the main channel and flow escaped over the banks with sufficient force to scour new meander bends into the floodplain surface.

Understanding how the channel responds to large flow events has helped prioritize restoration sites that will reduce sediment delivery to the mainstem, improve aquatic habitat, and restore natural flow conditions. The best opportunity for restoration is on the alluvial fan at the mouth of the Mohawk River where the Town of Colebrook owns land that can be used to return flow to its originally meandering channel. Future studies will determine how much sediment can be stored on the alluvial fan surface before entering the Connecticut River mainstem and what habitat benefits will result from recreating channel sinuosity, returning flow to abandoned side channels, and increasing flow complexity.

The morphology of the Upper Ammonoosuc River is also controlled by several human factors. Three dams are located in Groveton, NH and, in total, impound over 2.0 miles of river. Although bank erosion is observed immediately downstream of the dams, point bar development, channel migration, and continued floodplain access near the confluence with the Connecticut River mainstem indicate that the dams have not resulted in discernible channel incision. Upstream of the dams' influence, tributary inputs and channel straightening are the primary factors controlling channel morphology and bank stability. Sediment inputs from Nash Stream, a tributary that suffered a large dam break flood in 1969, completely transform the morphology of the Upper Ammonoosuc River. Upstream of the Nash Stream confluence the river is in a single deep and narrow channel that has remained unchanged since 1930 while downstream the multi-thread wide and shallow channel has shifted repeatedly as gravel bars fed by Nash Stream form and migrate down the river. Despite the presence of the dams, the influence of Nash Stream has extended to the Connecticut River mainstem where the growth of a sand bar is

partially responsible for flow deflection and bank erosion at the Northumberland Cemetery.

Tributary inputs elsewhere on the Upper Ammonoosuc are helping to recreate meanders along portions of the 33 percent of channel artificially straightened by humans. Growth of a gravel bar and alluvial fan at the mouth of Mill Brook in Stark, NH has caused the Upper Ammonoosuc River to shift up to 250 feet in more than 70 years as flow is diverted around the accumulating sediment. The resulting erosion on the bank opposite the Mill Brook confluence is currently threatening the North Side Road along which emergency repairs were required twice during 2005. Although erosion is found along only seven percent of the river's banks, bank instabilities also occur immediately downstream of straightened segments. Increased sediment transport capacity resulting from the straightening causes increased deposition and flow deflection in the meander bends downstream where the sediment transport capacity is reduced.

The Mill Brook confluence was selected as the highest priority site for restoration. As on the lower Mohawk River, restoring flow to abandoned side channels on the Mill Brook alluvial fan will simultaneously create nursery habitat while reducing sediment inputs to the receiving stream. While the reduction of sediment delivery from Mill Brook will have only a minimal impact on the Connecticut River, restoration of natural flow patterns on Mill Brook will alleviate erosive pressures on North Side Road and will demonstrate how to mitigate the impacts of tributary inputs elsewhere in the Connecticut River watershed.

## 1.0 INTRODUCTION

This report describes the results and recommendations of a fluvial geomorphology assessment of the Mohawk and Upper Ammonoosuc Rivers, two tributaries to the Connecticut River in New Hampshire (Figure 1). The Mohawk River has a drainage area of 56 mi<sup>2</sup> with the lower ten miles of the river assessed. The Upper Ammonoosuc River watershed is much larger (210 mi<sup>2</sup>) with the assessment extending a total of 22 miles from the North Branch confluence downstream to the river's mouth near Groveton, NH. Dams are present on both rivers and some of their tributaries. While the impact of dams on flow was greater in the past when more, now breached, dams were present, the rivers are currently free flowing within the assessed areas except for impoundments in Groveton, NH on the Upper Ammonoosuc. Mainstem bank erosion near tributary confluences was linked to sediment inputs from the tributaries during the 2004 *Fluvial Geomorphology Assessment of the Northern Connecticut River* (Field, 2004). The tributary assessments reported on here were completed to better understand sediment transport processes in the tributary watersheds and how human land use might be accelerating sediment delivery to the mainstem. A primary goal of the tributary assessments was to identify restoration opportunities that could not only improve channel stability on the tributaries but could also positively impact conditions on the Connecticut River.

The Connecticut River Joint Commissions has been working since 1989 to stem riverbank erosion on the Connecticut River. The Connecticut River Joint Commissions decided to undertake a fluvial geomorphology assessment of two northern Connecticut River tributaries in order to identify sediment sources and locations of sediment storage, because limiting the amount of sediment emanating from tributaries may lead to long term reductions in bank erosion on the mainstem. Fluvial geomorphology is a science that attempts to understand how river channels adjust their shape (width and depth) and planform (sinuosity/"windiness") through erosion and deposition to reach an equilibrium with natural conditions and human land use in the watershed. Restoring tributary watersheds to equilibrium conditions is a prerequisite to establishing and sustaining equilibrium on the Connecticut River. If instabilities on the tributaries remain untreated, the potential exists for problems to be transferred downstream and efforts to resolve problems on the mainstem rendered ineffective.

Recognizing the value of fluvial geomorphology to reduce erosion hazards and improve aquatic habitat, the State of Vermont has developed a three phase Stream Geomorphic Assessment Handbook to reveal the underlying causes for erosion and other riverine hazards (Vermont Agency of Natural Resources, 2003). Phase 1 of Vermont's Stream Geomorphic Assessment Handbook utilizes topographic maps, aerial photographs, and archival records to characterize natural conditions and human land uses in the watershed. Surveying and other fieldwork during Phase 2 of the assessment provides information on the existing morphology of the channel in each identified reach. Project designs are possible with the results of more detailed surveying during Phase 3. By comparing existing channel conditions with those that would be expected to develop in an undisturbed setting, the handbook can be used to better understand the natural and

human causes for channel instability (Phase 1), identify the most unstable and degraded reaches in a river system (Phase 2), and choose restoration strategies that will bring rivers towards a natural equilibrium condition (Phase 3).

The assessment of the northern Connecticut River tributaries employed the three phase handbook to accomplish five major goals discussed in turn below: 1) subdivide the rivers into distinct reaches; 2) define the major controls on channel morphology; 3) identify the natural conditions and human land uses increasing or reducing sediment production and sediment delivery to the mainstem; 4) develop strategies for reducing sediment production and increasing sediment storage in the tributary watersheds; and 5) design a conceptual restoration project at one high priority site on each tributary that employs one or more of the developed strategies for reducing sediment inputs to the Connecticut River mainstem. After a general introduction to each section, the results for each tributary are discussed separately where warranted. The Stream Geomorphic Assessment Handbook data are generally entered into a web-based management system administered by the State of Vermont River Management Program, but since the tributary assessments were conducted in New Hampshire the results were compiled on an Excel Spreadsheet (Appendix 1) and integrated into the report below. Steps 9 and 10 of the Phase 1 assessment are automated within Vermont's web-based data management system, so were not completed as part of this assessment. A number of channel features, including bank stability and composition, were mapped continuously along the lengths of the assessed tributaries and entered into a GIS database in order to supplement results of the assessment handbook (Appendix 2). The results of the mapping are summarized in Table 1 and discussed further below.

## **2.0 SUBDIVIDING REACHES**

Since different portions of a river might respond differently to the same natural and human factors, the first assessment task is to subdivide the river into distinct reaches. Within a given reach, the river is assumed to respond similarly to changing watershed conditions while adjacent reaches may respond differently. Reaches that share similar traits are referred to as "like-reaches" and an understanding of channel response or effective restoration techniques gained in one reach may apply to other "like-reaches". Break points between different reaches are made on the presence of one or more conditions, including natural changes in valley slope, constrictions of valley width, expansions of valley width, and the confluence of a major tributary. Reaches downstream of constrictions tend to occupy more confined valleys where the river channel has a greater likelihood of flowing against glacial sediments exposed along the high valley walls. The potential for high rates of sediment production in these locations can affect channel morphology differently than reaches occupying wide valleys where the channel encounters floodplain sediments only. Reaches downstream of tributary confluences will generally have a morphology different than reaches immediately upstream of the confluence because of the introduction of sediment at the confluence.

The morphological impacts of tributary confluences, as well as valley constrictions and expansions, are generally most noticeable at or near the reach break.



Consequently, the locations of the reach breaks themselves are likely points of channel instability with active bar formation, bank erosion, and channel migration possible. For example, mid-channel bars typically form just downstream of points of valley expansion where the stream power to carry the sediment is lost with flow expansion. Bars are also commonly observed downstream of tributaries because of the excess sediment added at the confluence. Delineating the reach breaks and understanding the morphological conditions present in each reach are critical for identifying the natural and human conditions leading to erosion and channel instability.

## **2.1 Mohawk River**

The Mohawk River was subdivided into seven reaches of uneven length using topographic maps (Figure 2a and Appendix 1). The reaches were numbered consecutively from the downstream end of the river and designated T4.01, T4.02, etc. to indicate that the reaches are located on the fourth major tributary of the northern Connecticut River upstream of the Gilman Dam in Gilman, NH (Figure 2a and Table 2). Three of the reach breaks occur at tributary confluences and three are found at points of flow expansion with the most significant expansion downstream of Reach Break T4.02 (i.e., in Reach T4.01) where the river debouches onto an alluvial fan within the Connecticut River Valley (Figure 3a). The remaining reach break (T4.01) is located at the confluence with the Connecticut River. No significant natural changes in valley slope occur along the length of the river. Of the seven identified reaches, a Phase 2 assessment was completed on four (Table 2).

## **2.2 Upper Ammonoosuc River**

The Upper Ammonoosuc River was subdivided into nine reaches of uneven length using topographic maps (Figure 2b and Appendix 1). The reaches were numbered consecutively from the downstream end of the river and designated T2.01, T2.02, etc. to indicate that the reaches are located on the second major tributary of the northern Connecticut River upstream of the Gilman Dam in Gilman, NH (Figure 2b and Table 2). Two of the reach breaks occur at tributary confluences, three are found at points of flow expansion, and three at valley constrictions. The Upper Ammonoosuc, like the Mohawk River, flows across an alluvial fan where the river enters the broad unconfined Connecticut River Valley (Figure 3b).

Significant changes in channel morphology are evident at the confluence of Nash Stream (Reach Break T2.04) with large gravel bars and braided channels present downstream in Reach T2.03 while a narrow single thread channel is present upstream in Reach T2.04 (Figure 4). The remaining reach break is at the confluence with the Connecticut River (T2.01). No significant natural changes in valley slope occur along the length of the river, but three dams are found in Reach T2.02 and impound water for the total length of the reach (Figure 3b). Of the nine identified reaches, a Phase 2 assessment was completed on four (Table 2).

### 3.0 MAJOR CONTROLS ON CHANNEL MORPHOLOGY

In the absence of human settlement, channel morphology (i.e., shape and planform) responds to natural conditions present in the watershed. Establishing the conditions present adjacent to the channel (e.g., soil type, valley confinement) and in the larger watershed (e.g., drainage area, forest cover) can help determine what channel morphologies would develop in the absence of human land use. Differences between the expected morphology under natural conditions and what morphology actually exists are generally an indication that human land use is altering channel morphology. The existing and expected morphological conditions within each reach on the northern Connecticut River tributaries were established by analyzing topographic maps and aerial photographs, surveying channel dimensions in the four selected Phase 2 reaches on each tributary, and mapping channel conditions continuously along the river's length (Appendices 1 and 2).

Several morphological parameters can be determined using current and historic topographic maps and aerial photographs, including sinuosity, slope, size and types of bars, and channel migration. Field surveys and mapping can provide additional information on channel dimensions, bed forms, and bank stability. The temporal and spatial distributions of morphological conditions on the tributary watersheds were used to identify five major controls on channel morphology: natural geological setting; artificial straightening; dams; tributary inputs; and large floods. Each factor is discussed further below.

#### 3.1 Natural Geological Setting

Rivers flowing through broad valleys typically have lower slopes, higher natural channel sinuosities, and greater rates of channel migration than those in more confined valley segments. The Mohawk River is generally more confined between bedrock and glacial outwash terraces while several reaches on the Upper Ammonoosuc River flow across a broad floodplain (Figure 5; Table 3; Appendix 1). Consequently, Mohawk River sinuosities are naturally less than 1.2 on all but the unconfined alluvial fan (as determined by the ratio of channel length/valley length) but exceed 1.7 in Reach T2.07 on the Upper Ammonoosuc, the only unconfined reach with limited human channel manipulation (Figure 5; Table 3; Appendix 1). Broad unconfined reaches with shallow slopes, marshy areas, and high sinuosities are a consequence of glacial erosion (Figure 5b). Glaciers and ice sheets are capable of scouring flat valleys that become highly meandering depositional zones as the river tries to achieve a more graded slope. Narrower valley segments on the Upper Ammonoosuc are generally confined by bedrock as at Devil's Slide in Stark (Reach T2.06; Figure 6a) but Reach T2.04 is unusual in that the northern valley wall is confined by ancient alluvial fan deposits of Nash Stream (Figure 6b). Overall, valley widths are much narrower on the Mohawk River and valley gradients much higher compared to the Upper Ammonoosuc (Table 3 and Appendix 1). While these differences are largely the result of the underlying bedrock geology, the Mohawk River Valley is further confined by glacial outwash terraces inset within the bedrock ridges (Figure 5a).

Natural channel migration during the map record (the earliest topographic maps for the two tributaries were surveyed in 1930) is limited to unconfined reaches. Despite the presence of dams upstream, the most significant channel changes have occurred on the alluvial fan of the Upper Ammonoosuc (Reach T2.01; Figure 3b and Appendix 1). Both meander growth and meander cutoffs are observed (Figure 7). In addition, numerous abandoned side channels are evidence of channel migration prior to the earliest maps (Figure 3b and 7). Changing vegetation patterns in the side channels indicate that these channels are reactivated during large flood events (Field, 2006).

### **3.2 Artificial Straightening**

Many of the naturally meandering channels formed in broad valley reaches have been artificially straightened by humans with the remnant oxbows of the former channels still visible in many places (Figure 8). As much as 50 percent of the Mohawk River was artificially straightened prior to 1900, although some occurred much later (Figure 9). The earlier straightening is most likely related to agricultural practices and log drives while the straightening on the lower Mohawk River was completed by the Army Corps of Engineers in the 1960's to reduce ice jams and flooding in Colebrook (Kevin McKinnon, 2005, personal communication). A total of 33 percent of the Upper Ammonoosuc was straightened prior to 1900 with over 65 percent of Reaches T2.05 and T2.09 affected (Table 3 and Appendix 1).

Straightened channels are typically devoid of sand and gravel bars with a plane bed morphology predominating. In contrast, adjacent meandering segments have point bars and a pool riffle morphology (Figure 8). To further detail the morphological differences between meandering and straight segments of unconfined reaches, cross sections were surveyed across a meandering and straight portion of the channel on the Upper Ammonoosuc alluvial fan (Reach T2.01). The bankfull width and area of the straightened channel are greater than the nearby meandering segment but the depth is lower, leading to shallower flows (Figure 10). While some of the increased width in the straightened segment may be due to its location immediately downstream of the dams (see Section 3.3 below), the findings are consistent with comparisons between straightened and meandering channels completed on the northern Connecticut River (Field, 2004).

### **3.3 Dams**

Three dams are present in Reach T2.02 on the Upper Ammonoosuc River with the entire 2.0 mile reach impounded (Figure 3b and Appendix 3). A fourth dam is located in the upper watershed beyond the assessed area. In the Mohawk River watershed, five small earthen dams are present in the upper watershed but also beyond the extent of the assessment (Appendix 3). Sediment accumulation behind Red Dam has created a network of distributary channels as sediment is deposited on a delta at the upstream end of the impoundment (Figure 11). The channel migration observed on aerial photographs in this reach is the result of the continuing accumulation of sediment that fills the channel and shifts the flow into a new channel lower on the delta surface (Appendix 1).

Downstream of Weston Dam, bank erosion of very loose alluvial fan gravels is observed along both banks (Figure 12). While the erosion may be the result of a sediment deficit below the dams, the possibility that the bank instability is the result of channel straightening cannot be discounted (see Section 3.2 above). The presence of large unvegetated sand bars further downstream in Reach T2.01 near the confluence with the Connecticut River suggests that any sediment deficit below the dam does not persist for any great distance downstream (Figures 7b and 10a).

In addition to the existing dams, a number of other dams were once present on both rivers and are currently in various states of disrepair (Figure 13; Appendix 3). Some that are only partially breached, such as the Washburn Mill Dam on the Mohawk River, have large mid channel bars formed behind them (Figure 13). Mid channel bars also persist in locations where dams are now completely absent, but the dams might be responsible for the initial bar formation (Figure 14a). One dam in each watershed failed catastrophically and resulted in large floods that had dramatic morphological impacts on the channel as discussed in Section 3.6 below.

### 3.4 Tributary Inputs

Similar to the results of the Connecticut River assessment, tributary inputs exert an influence on the morphology of the Upper Ammonoosuc River. (Tributary inputs were not documented to have an impact on the Mohawk River, perhaps because of the narrower valley and greater channel confinement). The morphology of the Upper Ammonoosuc is completely transformed at the confluence of Nash Stream. Gravel inputs from Nash Stream (Figure 2b) form large gravel bars downstream that result in the creation of braided flow conditions (Figures 4, 14, and 15). With gravel deposition, flow escapes from the channel and creates vegetated islands as new channels are scoured across the floodplain (Figure 16). The vegetated islands represent remnant portions of the floodplain isolated by the scouring of new channels. Upstream of the confluence, the channel is confined between Beach Hill and ancient Nash Stream alluvial fan deposits (Figure 6b). Unable to erode laterally at this location (Reach T2.04), the river is naturally straight, has scoured a deep channel, and has not migrated laterally since at least 1930 (Figures 14 and 16a). Consequently, the channel downstream of the confluence has a much higher width:depth ratio compared to upstream (Figure 16).

Elsewhere on the Upper Ammonoosuc River, tributary inputs are responsible for recreating meanders on previously straightened channel segments (Figure 8). As sediment is deposited at the mouth of the tributary, flow on the Upper Ammonoosuc is deflected into the opposite bank. Erosive pressures on the opposite bank lead to bank instabilities and bank armoring if infrastructure is threatened as at the Mill Brook confluence (Figure 17). The amount of channel migration resulting from this process appears to be related to the size of the tributary responsible for sediment inputs. Mill Brook has shifted over 250 feet from the position of the channel immediately after straightening while the smaller tributaries to the west have migrated less than 100 feet (Figure 8).

### 3.5 Large Floods

The tributary impacts on channel morphology discussed above are ultimately the result of large flow events capable of transporting sediment to the stream's confluence. The Upper Ammonoosuc downstream of Nash Stream was transformed from a single thread channel to a braided channel with large mid channel bars between 1930 and 1955, perhaps during the 1936 flood event (Figure 14a-b). The only mid channel bar on the 1930 map is at the location of an old dam no longer present (Figure 14a). The 1936 flood probably reopened a number of side channels that already existed prior to the flood but were not visible when the 1930 map was surveyed due to revegetation that occurred during several years with no large floods. The braided channel configuration below Nash Stream was further enhanced by another large flood in 1969 caused by the breaching of the Nash Stream Bog Dam (Figure 2b). Sand sheets deposited on the Nash Stream alluvial fan during the dam break flood are clearly visible on the 1970 aerial photograph, but the channel configuration downstream on the Upper Ammonoosuc remained relatively unchanged from 1955 (Figure 14b-c). No significant floods of comparable magnitude have occurred since 1969 and a number of side channels have consequently become revegetated (Figure 14d).

The effects of the 1936 and 1969 floods extended to the Connecticut River mainstem despite the three dams in Groveton. Short sawed logs from former log drives on the Upper Ammonoosuc are buried in the bank in Reach T2.01 near the mouth of the Upper Ammonoosuc (Figures 10a and 18). Their presence indicates that some material passes the dam during large floods. In addition, the sand bar just upstream of the Northumberland Cemetery on the Connecticut River first appeared and grew in size during the time period 1930-1970, apparently due to sediment emanating from the side channel on the Upper Ammonoosuc alluvial fan (Figure 3b; Field, 2006). The bar diminished in size after 1970 – the same time frame in which no large floods have occurred and side channels on the Upper Ammonoosuc (Reach T2.03) have become revegetated (Figure 14c-d; Field, 2006). The timing of changes on the sand bar suggests sediment also passes the dams during large floods, perhaps when side channels on the Upper Ammonoosuc alluvial fan are reactivated (Figure 3b).

While the morphology of previously straightened channels on the Mohawk River remains relatively unchanged during small to moderate floods, the catastrophic failure of the Lake Abenaki Dam in Dixville in 1929 caused the resulting floodwaters to “break out” with enough stream power to carve new meanders across the floodplain in several places (Figures 19 and 20). “Break outs” tend to occur where the channel becomes clogged with woody debris or sediment. The “break outs” represent another process by which the channel regains sinuosity and approaches an equilibrium condition; tributary inputs being the other process as discussed above. The straightened segments cut off by the meanders are now abandoned except at one location where flow returned to the existing channel and the newly created meander was abandoned. While the abandoned straightened channels can still be observed on aerial photographs (Figure 19), these segments have been filled in many places and are hard to recognize in the field (Figure 21).

The morphology of the newly created meanders is characterized by large gravel bars, flood chutes, and an emerging pool riffle bed form (Figure 20). Adjacent straightened channels have a plane bed morphology with little bar formation. As flow escapes onto the floodplain, the sediment carrying capacity of the stream is lost and the sediment forms bars. The flow, now devoid of sediment, has the capacity to scour the floodplain, forming a new channel and, in some cases, additional flood chutes that run through the floodplain vegetation.

#### **4.0 SEDIMENT PRODUCTION AND DELIVERY**

The morphological conditions and controls described above provide insights to the mechanisms by which sediment is produced in the watersheds and ultimately transferred to the Connecticut River mainstem. The 2004 *Fluvial Geomorphology Assessment of the Northern Connecticut River* identified unnaturally high rates of sediment inputs from tributaries as a major cause for bank erosion (Field, 2004). An understanding of why excess sediment is delivered to the mainstem will help to not only resolve erosion problems on the Connecticut River but could also improve channel stability within the tributary watersheds themselves. Sediment delivery is ultimately a combination of the processes that produce sediment in the watershed and those that transport the sediment through the watershed to its mouth. Given differences in the relative importance of these processes on the Mohawk and Upper Ammonoosuc Rivers, the two watersheds are discussed separately below.

##### **4.1 Mohawk River**

###### *4.1a – Sediment production*

Although bank erosion occurs along only ten percent of the Mohawk River (Table 1 and Appendix 2), the dam break flood in 1929 destabilized high banks of glacial deposits in many locations along the Mohawk River (Figure 22). Although triggered by a large flood, the bank instability has been sustained in some locations by smaller floods and the erosion continues to this day, precipitating the construction of rock gabions nearly eighty years after the flood (Figure 23a). Sediment shed from these high slopes is deposited on bars immediately downstream with deflection of flow around these bars causing further erosion (Figure 23b). Consequently, while sediment eroded directly from the high unstable banks may not be transported to the Connecticut River, the high rate of sediment production from the high bank can begin a cascade of instabilities that eventually lead to additional sediment reaching the mainstem.

A number of other sediment sources are present in the Mohawk watershed. In addition to the ten percent of the river banks classified as eroding, another 13 percent of the banks on the Mohawk River are moderately eroding (Appendix 3). Since 80 percent of the river's banks are composed of alluvial (i.e., floodplain) soils, most of the erosion or moderate erosion occurs along low banks (Table 1 and Appendix 2). Large point sources of sediment are, thus, produced at any only a few high unstable banks (Figure 23a).

However, the cumulative effect of small amounts of sediment derived from 25 percent of the river's length could also lead to excessive sedimentation at the river's mouth. Although tributaries were not seen to greatly impact the river's morphology, some sediment is also derived from the numerous small tributaries that enter the Mohawk River from the north and south (Figure 2a). Finally, sediment impounded behind breached dams would become another source of inputs to the Connecticut River if the dams deteriorate further (Figure 13).

#### *4.1b – Sediment Delivery*

Sediment derived in the Mohawk River watershed must be transferred to the mouth if it will ultimately impact the Connecticut River mainstem. Several natural conditions and human land uses favor sediment transport downstream over floodplain storage in the watershed. Eight percent of the Mohawk River's banks encounter bedrock along the narrow valley. Artificial armoring (i.e., riprap) along 13 percent of the banks further enhances the transport of sediment down the constricted and armored valley (Table 1 and Appendix 2). Concrete and rock riprap line a large percentage of the channel on the alluvial fan at the mouth of the river (Reach T4.01; Figure 24). Roads and berms, although directly impacting the stream in only a few places, also increase the stream's sediment transporting efficiency by virtue of the higher velocities created as the flow passes through the constricted areas (Figure 25). Artificially straightened channels on the Mohawk River have a higher slope than their meandering counterparts. The higher sediment transport efficiency of the straightened channel results in a plane bed morphology with limited bar formation. Gravel bars are found only where the channel has broken out across the floodplain and formed new meanders. A return to natural flow patterns would lead to greater sediment storage in the Mohawk River watershed with deposition resulting from the attenuation of flows within meanders formed on the floodplain.

### **4.2 Upper Ammonoosuc River**

#### *4.2a – Sediment production*

Sediment production from tributaries is high in the Upper Ammonoosuc watershed with Nash Stream completely transforming the morphology of the channel upstream and downstream of the confluence (Figures 4 and 16). Channel migration in each reach downstream of the Nash Stream confluence is driven by the sediment delivered to the Upper Ammonoosuc (Figures 7, 11, and 14). As with the 1929 dam break flood on the Mohawk River, the 1969 dam break flood on Nash Stream destabilized several high banks of glacial outwash deposits that continue to contribute sediment to the stream over 35 years after the flood. Berming and straightening completed after the flood to protect roads along Nash Stream have constricted flows in the channel such that the base of the high banks are frequently scoured and the banks are unable to stabilize. Tributary inputs from other streams are also high. Sediment from the tributaries is what drives the recreation of meanders along previously straightened segments and creates instabilities that are transferred downstream (Figures 8 and 17).

Tributary inputs from above Nash Stream (e.g., Mill Brook in Reach T2.05) probably contribute very little to the Connecticut River with much of the sediment deposited and stored on the floodplain or in gravel bars above Nash Stream. Conditions on Nash Stream, with high rates of sediment production, currently dictate conditions on the lower Upper Ammonoosuc (Reaches T2.01-T2.03) and sediment supply to the Connecticut River.

Channel straightening on the Upper Ammonoosuc has focused the river's energy during high flows at "hard" bends along the channel where the end of a straightened segment rejoins the naturally meandering channel (Figure 8). Where these hard bends are coincident with high banks of glacial outwash deposits, the resulting instability generates additional sediment in the channel (Figure 26).

#### *4.2b – Sediment Delivery*

In contrast to the Mohawk River, conditions on the Upper Ammonoosuc tend to limit sediment delivery to the Connecticut River. Although sediment delivery is high through straightened (Figure 8) and armored reaches (13 percent of the banks are riprapped), many natural meandering sections remain on the Upper Ammonoosuc, especially at the confluence (Figure 3b). Sediment stored on point bars within the meander bends (Figures 7, 8, and 10) and mid channel bars in braided sections (Figures 11 and 14) limits sediment delivery and ameliorates impacts to the Connecticut River. Sediment does reach the Connecticut River during high discharges, but the sand bar on the Connecticut River below the confluence has diminished in size since 1970 – a period with no large floods (Field, 2006). In contrast, the mid channel bar downstream of the Mohawk River confluence has grown in size during the same time period (Figure 9).

The presence of dams on the Upper Ammonoosuc disrupts the natural transfer of sediment to the Connecticut River mainstem. Large volumes of sediment are stored behind the dams in Groveton, NH (Figure 11). In 2005, initial discussions were held regarding the removal of Red Dam. While removal is no longer a consideration, future investigation of dam removals on the Upper Ammonoosuc should consider the impact stored sediment behind the dams might have on downstream morphology and bank stability, including on the Connecticut River downstream of the confluence.

Natural grade controls and rejuvenation points along the channel further limit the transfer of sediment throughout the river system to the Connecticut River. Sediment inputs from Nash Stream rejuvenate the river downstream such that conditions on the Upper Ammonoosuc above Nash Stream exert little influence on the Connecticut River. Valley constrictions such as in Stark, NH (Reach T2.06; Figures 2b and 6a) also serve as grade controls with conditions upstream of the constriction not transferred through the constriction to downstream reaches. The river channel has a sandy substrate with dune-ripple morphology above the constriction (Reach T2.07) but below the constriction a gravel substrate with plane bed morphology predominates (Appendix 2). The energy and sediment derived from the steeper constricted valley exerts a far greater influence on downstream conditions than the water and sediment passing through the constricted reach



from upstream. Human land uses in the upper watershed that increase sediment production or enhance sediment delivery downstream will not alter conditions along the entire Upper Ammonoosuc River as their impact will be limited by the natural grade controls and rejuvenation points. In contrast, the absence of significant grade controls on the Mohawk River means that human land uses in the upper watershed can alter the morphology and sediment transfer along the entire length of the river.

## **5.0 STRATEGIES FOR REDUCING SEDIMENT PRODUCTION OR INCREASING SEDIMENT STORAGE**

Sediment inputs from tributaries were identified as a significant cause for bank erosion on the Connecticut River during the 2004 *Fluvial Geomorphology Assessment of the Northern Connecticut River* (Field, 2004). Bank stability on the Connecticut River, therefore, can be improved by reducing sediment production or increasing sediment storage in the tributary watersheds. An understanding of the natural processes in the watershed and how the river responds to human land use provides insights to management strategies capable of limiting sediment inputs to the Connecticut River.

### **5.1 Reducing Sediment Production**

The most obvious sediment sources in the tributary watersheds are from high eroding banks of glacial outwash deposits (Figures 23a and 26) and inputs from tributary streams (Figures 4 and 8). Limiting the amount of sediment emanating from the secondary tributaries would require stabilizing sediment sources or storing sediment in the tributary watershed, so management strategies for dealing with tributary inputs closely mirror those appropriate for the larger tributaries of the Connecticut River. High banks of glacial outwash deposits could be stabilized with various bioengineering techniques that use logs and other organic material to support the base of the slope, baffle and deflect flow away from the bank, and prevent the bank from being undercut. Anchoring debris at the base of a high unstable slope is, however, difficult, costly, and prone to failure. Rock revetments at the base of the slope will limit sediment inputs to the stream, but such riprap can have negative habitat impacts and are also prone to failure. Where the high banks are unstable due to channel straightening upstream (Figure 26), a realignment of the channel's flow path into former oxbows could remove the erosive pressures at the base of the bank. However, realigning a channel is often difficult under current land ownership and can lead to unintended channel responses that lead to additional instabilities. In some instances, a high bank was destabilized as a result of the channel recreating meanders along a previously straightened segment (Figure 23a). Returning the channel to the abandoned straightened segment would reduce erosive pressures on the high bank but would increase the channel's sediment transport capacity and return the channel to a morphological condition that is unstable during large floods.

### **5.2 Increasing Sediment Storage**

While some high eroding banks could potentially be stabilized, many other sediment sources in the tributary watersheds are very diffuse and distributed throughout

the drainages. Attempting to stabilize all of these sources would be too impractical, costly, and time consuming. A more feasible approach to reducing sediment inputs to the Connecticut River is to increase sediment storage on bars and the floodplain. Straightened segments naturally respond to large floods by establishing new meanders as the flow “breaks out” across the floodplain with large gravel bars forming in the newly established meanders (Figures 19 and 20). Reestablishing sinuosity by returning flow to abandoned meanders along straightened segments could lead to the deposition of gravel bars (e.g., abandoned oxbows and meanders in Figures 8 and 19). Implementation of such a management strategy would not only reduce sediment transfer downstream to the Connecticut River but might also reduce the risk of unplanned “break outs” that might impact human infrastructure or destabilize high banks along the valley margins. However, heavy land use in the valley bottom will likely conflict with the reestablishment of channel sinuosity in most locations.

## **6.0 CONCEPTUAL RESTORATION PROJECT DESIGNS**

The current study of the Mohawk River and Upper Ammonoosuc River was undertaken to identify potential restoration sites that could improve channel stability on the tributaries and reduce bank erosion on the Connecticut River at the Colebrook Business Park and Northumberland Cemetery (Figure 2). Stabilizing sites of sediment production or enhancing locations of sediment storage in the tributary watersheds could ultimately lead to long term reductions in sediment inputs, and in turn, improve bank stability on the Connecticut River. Several restoration sites were considered with a Phase 3 assessment conducted and conceptual restoration design options developed for the chosen restoration priority in each tributary. In addition to the likelihood for reducing sediment inputs to the Connecticut River, potential restoration sites were prioritized in terms of habitat benefits, ability to improve channel stability within the tributary, long term sustainability, landowner willingness, and public support.

### **6.1 Mohawk River – Lower Mohawk River**

The alluvial fan on the lower Mohawk River (Reach T4.01) was chosen as the priority restoration site in the Mohawk River watershed (Figure 27). Channel straightening through this reach in the 1960’s led to the growth of gravel bars on the Connecticut River that have contributed to bank erosion at the Colebrook Business Park (Figure 9). The gravel bars have grown downstream of the confluence, because channel armoring to protect Vermont Route 102 on the bank directly opposite the confluence constricts the flow and forces most of the sediment further downstream. A small gravel bar is, however, found at the confluence (Figures 9b and 27).

Five management options were considered for reducing sediment loads on the Connecticut River: do nothing; remove the gravel bar at the mouth of the Mohawk River; engineer a meandering channel that trends along the current flow path; restore flow to abandoned side channels south of the current channel; and restore flow to abandoned side channels north of the current channel. A conceptual plan view design and list of pros and cons were developed for each option (Appendix 4). Removing the gravel bar at the

mouth of the Mohawk River will create a sediment budget deficit that may lead to the scouring of bars downstream at the Colebrook Business Park. However, with the straightened configuration of the lower Mohawk River unchanged, the removed sediment will be quickly replaced and improvements to bank stability at the Business Park not sustained. The excavation of new meanders along the straightened channel will promote the deposition of gravel bars on the Mohawk River, but even with careful and costly engineering the creation of stable meanders is difficult. Consequently, unplanned instabilities could result. While restoring flow to the side channels south of the current channel would increase the length of the channel and, therefore, promote deposition, several homes are located near the southern margins of the alluvial fan (Figure 27). Although the houses are on ancient alluvial fan deposits elevated sufficiently above the side channels to prevent flooding, landowner concern and unwillingness should be anticipated for any plan that brings the river closer to the homes.

Restoring flow to the side channels on the north side of the current channel is the favored option for managing the site. More space is available for restoration to the north and flow could enter the Connecticut River at multiple locations rather than at the current single location. Spreading flow out over multiple paths will lead to the deposition of sediment before it enters the Connecticut River, reduce flow velocities impacting the rock revetment protecting Vermont Route 102 on the opposite side of the Connecticut River, and create side channel rearing habitat and wetlands for the diverse fish and waterfowl species found on the Connecticut River. Flow could be returned to the side channels by blocking flow in the current channel with an engineered log jam and would not require extensive excavation of new flow paths. Since natural flow conditions would be restored, the reduction in sediment inputs to the Connecticut River and resulting habitat improvements would be sustainable over the long term.

While sediment storage could be achieved elsewhere in the watershed where the channel has been artificially straightened, improvements to channel stability will be greatest immediately adjacent to a given project site. Therefore, in an effort to reduce sediment inputs and the resulting erosion on the Connecticut River, the lower Mohawk River is the best site for restoring natural flow patterns that will induce deposition and long term sediment storage. Furthermore, the Town of Colebrook, which owns the land on the alluvial fan, supports the conceptual design and is interested in pursuing further feasibility studies. Before implementation, hydraulic modeling is needed to establish the amount of sediment storage that will occur with a reconfiguration of flow paths and to determine if increased flooding might jeopardize human infrastructure in Colebrook, particularly the sewage treatment ponds (Figure 27).

## **6.2 Upper Ammonoosuc River – Mill Brook Confluence**

The Mill Brook confluence (Reach T2.05) was chosen as the priority restoration site in the Upper Ammonoosuc watershed (Figure 28). Sediment inputs from Mill Brook in Stark, NH have caused over 250 feet of erosion on the opposite bank since the Upper Ammonoosuc River was straightened, probably in the 19<sup>th</sup> Century (Figure 8). The sediment deposition and subsequent erosion have created a gentle meander bend along

the previously straightened channel. Current land uses and channel configurations on Mill Brook (e.g., lower Mill Brook was straightened) still favor the generation and transport of sediment to the brook's mouth, so bank erosion on the Upper Ammonoosuc continues to this day. Emergency road repairs were made on North Side Road twice in 2005 (Figures 17 and 28) and residents of Stark remain concerned about continued erosion and flooding that results when sediment from Mill Brook creates a temporary damming effect on the Upper Ammonoosuc.

Five management options were considered for reducing sediment inputs from Mill Brook and limiting erosion hazards on the opposite bank: do nothing; relocate the road away from the bank; protect the eroding bank using bioengineering techniques; engineer meanders on the straightened segment of lower Mill Brook; and restore flow to side channels on the Mill Brook alluvial fan. A conceptual plan view design and list of pros and cons were developed for each option (Appendix 5). Relocating the road north of the railroad tracks will eliminate immediate concerns for road safety, but will be prohibitively expensive and legally complicated because of private landownership. In addition, doing nothing to reduce sediment inputs from Mill Brook will result in continued flooding in Stark and sustain channel instabilities that have led to the bank erosion and degraded habitat found throughout much of Reach T2.05. Protecting the riverbank with bioengineering techniques will provide short term protection for the road and create good cover habitat, but the project will not be sustainable because continued sediment inputs from Mill Brook will keep erosive forces focused on the bank. The excavation of new meanders along the straightened segment of lower Mill Brook will promote the deposition of gravel bars and reduce sediment inputs to the Upper Ammonoosuc. However, the creation of stable meanders is difficult to accomplish and unplanned for instabilities could result in new areas of erosion and sediment production.

Restoring flow to the side channels on the east side of the current channel is the favored option for managing the site. Splitting the flow into several longer flow paths will lead to deposition of sediment before it enters the Upper Ammonoosuc. This will reduce erosive pressures, because flow on the Upper Ammonoosuc will be capable of transporting the reduced sediment load away from the confluence before it deflects into the opposite bank. As with the lower Mohawk River restoration project described above, reestablishing side channel access will create rearing habitat and wetlands for fish and waterfowl. Flow could be returned to the side channels by blocking flow in the current channel with an engineered log jam and would not require extensive excavation of new flow paths. Since natural flow conditions would be restored, the reduction in sediment inputs to the Upper Ammonoosuc and resulting habitat improvements would be sustainable over the long term.

Restoration at the Mill Brook confluence has public support, initial landowner interest, and the potential to reduce erosive pressures on North Side Road while improving aquatic habitat. Since the Mill Brook confluence is upstream of the Nash Stream confluence, reductions in sediment load to the Upper Ammonoosuc from Mill Brook are unlikely to have a great effect on sediment delivery to the Connecticut River. However, human land use and development in the valley downstream of the Nash Stream

confluence precludes the implementation of restoration projects, except on the Upper Ammonoosuc alluvial fan (Reach T2.01) where natural flow conditions still persist and restoration is not warranted. As landowner willingness and public support for restoration grow in areas downstream of Nash Stream, successful restoration of natural flow patterns on lower Mill Brook could provide a model for additional projects on the Upper Ammonoosuc or Nash Stream that ultimately will lead to reductions in sediment inputs to the Connecticut River.

## 7.0 CONCLUSIONS

A fluvial geomorphic assessment of the Mohawk River and Upper Ammonoosuc River has revealed the major natural and human factors controlling sediment inputs to the Connecticut River. On the Mohawk River, the naturally constricted valley, artificial channel straightening, road construction, berming, and channel armoring all serve to increase the stream's effectiveness in transporting sediment to the river's mouth. While only ten percent of the banks are eroding, a large dam break flood in 1929 destabilized high banks of glacial outwash deposits that continue to be a source of sediment decades later (Figure 23a). The reestablishment of meanders in response to large floods provides areas for long term sediment storage that limit inputs to the Connecticut River. Encouraging meander formation in unsettled areas in the future could help to prevent flood damages by reducing the risk of meanders forming near human infrastructure. The sediment stored in the meanders will also improve bank stability on the Connecticut River by reducing the total volume of sediment reaching the mainstem. Reestablishing meanders on the lower Mohawk River (Figures 3a and 27) by returning flow to abandoned side channels has been identified as the highest priority restoration project, because its proximity to the Connecticut River will ensure greater and faster improvements to mainstem channel stability while reducing flood risks and improving aquatic habitat on the Mohawk River.

In contrast to the Mohawk River, natural and human factors on the Upper Ammonoosuc River tend to reduce the river's ability to transport sediment to the Connecticut River. While 33 percent of the river has been artificially straightened, the lower Upper Ammonoosuc River remains naturally meandering with large point bars storing considerable volumes of sediment (Figures 3b and 7). In addition, large volumes of sediment are stored in the impoundments behind three dams in Groveton, NH (Figure 11), although sediment does reach the Connecticut River during large floods. Natural valley constrictions tend to limit the passage of sediment from wider valley reaches upstream such that sediment from upstream of the Nash Stream confluence contributes little to the amount of sediment reaching the Connecticut River. A dam break flood on Nash Stream in 1969 delivered large amounts of sediment to the Upper Ammonoosuc River and reinforced morphological changes to the channel that resulted from the 1936 flood. The Nash Stream flood also destabilized numerous high banks of glacial outwash deposits that continue to contribute sediment to the Upper Ammonoosuc and control channel morphology downstream.

The Mill Brook confluence with the Upper Ammonoosuc in Stark, NH was chosen as the highest priority site for restoration, because public support is high for river management techniques that will reduce erosion on North Side Road caused by sediment inputs from Mill Brook (Figure 28). Restoring flow to abandoned side channels on Mill Brook will encourage the formation of gravel bars on the Mill Brook alluvial fan, decrease sediment delivery to the Upper Ammonoosuc, ease erosive pressures on North Side Road, and create aquatic habitat and wetlands. Although reductions in sediment inputs from Mill Brook will have only a minimal impact on the Connecticut River, the restoration techniques modeled might be applied later on Nash Stream and lower on the Upper Ammonoosuc when public support grows for such management strategies. While the purpose of the current study was to understand and limit sediment inputs to the Connecticut River, the assessment data (Appendix 1) and GIS mapping (Appendix 2) provide information that will prove useful in the future for understanding and managing river stability issues on the Mohawk and Upper Ammonoosuc Rivers themselves.

## **8.0 REFERENCES**

- Field, J., 2004, Fluvial geomorphology assessment of the northern Connecticut River: Unpublished report submitted to the Connecticut River Joint Commissions.
- Field, J., 2006, Bank stabilization implementation and assessment of the Connecticut River near Colebrook and Groveton, New Hampshire: Unpublished report submitted to the Connecticut River Joint Commissions.
- Vermont Agency of Natural Resources, 2003, Vermont Stream Geomorphic Assessment Handbook: Unpublished report available at [http://www.anr.state.vt.us/dec/waterq/rv\\_geoassesspro.htm](http://www.anr.state.vt.us/dec/waterq/rv_geoassesspro.htm).

## **Mohawk River Channel Morphology Statistics**

<b><u>Feature/Characteristic</u></b>	<b><u>Left Bank Length (ft)</u></b>	<b><u>% Length</u></b>	<b><u>Right Bank Length (ft)</u></b>	<b><u>% Length</u></b>	<b><u>Channel/Totals Length (ft)</u></b>	<b><u>% Length</u></b>	<b><u># of Features</u></b>
Length of channel	-	-	-	-	55,130	100.0	
Length of channel banks	55,893	100.0	55,362	100	111,255	100.0	
<b><u>Bank Height</u></b>							
0-5 feet	23,314	41.7	23,593	42.6	46,907	42.2	
6-10 feet	24,275	43.4	23,437	42.3	47,712	42.9	
11-20 feet	6,027	10.8	5,058	9.1	11,085	10.0	
20+ feet	2,272	4.1	3,274	5.9	5,546	5.0	
<b><u>Bank Composition</u></b>							
Alluvial	44,212	79.1	44,044	79.6	88,256	79.3	
Non-alluvial	6,803	12.2	7,489	13.5	14,292	12.8	
Bedrock	4,877	8.7	3,832	6.9	8,709	7.8	
<b><u>Bank Stability</u></b>							
Eroding	7,315	13.1	4,214	7.6	11,529	10.4	
Moderately eroding	9,199	16.5	5,392	9.7	14,591	13.1	
Armoring	6,412	11.5	8,539	15.4	14,951	13.4	
Stable	32,959	59.0	37,216	67.2	70,175	63.1	
<b><u>Riparian Buffer Width</u></b>							
0-10 ft	14,939	26.7	19,680	35.55	34,619	31.1	
11-25 ft	1,621	2.9	6,012	10.86	7,633	6.9	
26-50 ft	13,901	24.9	2,613	4.72	16,514	14.8	
51-75 ft	2,989	5.3	3,141	5.67	6,130	5.5	
76-100 ft	1,684	3.0	4,465	8.07	6,149	5.5	
101-125 ft	637	1.1	1,549	2.80	2,186	2.0	
126-150 ft	478	0.9	3,062	5.53	3,540	3.2	
>150 ft	19,642	35.1	14,843	26.81	34,485	31.0	
<b><u>Depositional Features</u></b>							
Point Bars	2,003	3.6	2,086	3.8	4,089	3.7	
Midchannel Bars	357	0.6	1,286	2.3	1,643	1.5	
<b><u>Channel Morphology</u></b>							
Cascade					402	0.7	
Step-pool					7,337	13.3	
Plane-bed					21,378	38.8	
Pool-riffle					26,013	47.2	
<b><u>Substrate Particle Size</u></b>							
Bedrock					1,065	1.9	
Cobble					3,064	5.6	
Gravel					51,000	92.5	
<b><u>Point Features</u></b>							
Breached dams							1
Bridges							16
Woody debris jams							11
Large woody debris							39

## Upper Ammonoosuc Channel Morphology Statistics

<u>Feature/Characteristic</u>	<u>Left Bank Length (ft)</u>	<u>% Length</u>	<u>Right Bank Length (ft)</u>	<u>% Length</u>	<u>Channel/Totals Length (ft)</u>	<u>% Length</u>	<u># of Features</u>
Length of channel	-	-	-	-	118,324	100.0	
Length of channel banks	120,631	100.0	119,725	100	240,356	100.0	
<u>Bank Height</u>							
0-5 feet	19,885	16.5	68,509	57.2	88,394	36.8	
6-10 feet	83,538	69.3	42,709	35.7	126,247	52.5	
11-20 feet	12,857	10.7	6,444	5.4	19,301	8.0	
20+ feet	4,351	3.6	2,061	1.7	6,412	2.7	
<u>Bank Composition</u>							
Alluvial	111,021	92.0	110,050	91.9	221,071	92.0	
Non-alluvial	8,859	7.3	9,487	7.9	18,346	7.6	
Bedrock	750	0.6	188	0.2	938	0.4	
<u>Bank Stability</u>							
Eroding	8,710	7.2	9,087	7.6	17,797	7.4	
Moderately eroding	13,979	11.6	14,965	12.5	28,944	12.0	
Riprap	15,857	13.1	14,175	11.8	30,032	12.5	
Stable	82,083	68.0	81,503	68.1	163,586	68.1	
<u>Riparian Buffer Width</u>							
0-10 ft	16,094	13.3	13,350	11.2	29,444	12.3	
11-25 ft	9,901	8.2	7,292	6.1	17,193	7.2	
26-50 ft	9,937	8.2	17,485	14.6	27,422	11.4	
51-75 ft	3,376	2.8	8,468	7.1	11,844	4.9	
76-100 ft	8,149	6.8	2,950	2.5	11,099	4.6	
101-125 ft	1,240	1.0	5,017	4.2	6,257	2.6	
126-150 ft	5,799	4.8	3,835	3.2	9,634	4.0	
>150 ft	66,136	54.8	61,330	51.2	127,466	53.0	
<u>Channel Morphology</u>							
Braided					5,365	4.5	
Cascade					3,274	2.8	
Plane-bed					53,823	45.5	
Pool-riffle					29,176	24.7	
Dune-ripple					26,687	22.6	
<u>Substrate Particle Size</u>							
Cobble					4,992	4.2	
Gravel					53,724	45.4	
Sand					59,607	50.4	
<u>Point Features</u>							
Dams							3
Bridges							15
Woody debris jams							1
Isolated wood							81

Note: Depositional features on Upper Ammonoosuc River not mapped



## Reach Break Locations

<u>Reach ID</u>	<u>Downstream Point</u>	<u>Upstream Point</u>	<u>Reason for Reach Break</u>	<u>Phase 2 Assessment Completed?</u>
<u>Mohawk River</u>				
T4.01	Connecticut River confluence	Colebrook Country Club on Rt. 26 in Colebrook	Confluence	Yes
T4.02	Colebrook Country Club on Rt. 26 in Colebrook	1/4 mile downstream of Fish Hatchery Rd	Expansion	No
T4.03	1/4 mile downstream of Fish Hatchery Rd	Confluence of unnamed stream w/ fish hatchery	Expansion	Yes
T4.04	Confluence of unnamed stream w/ fish hatchery	350 ft downstream of Carleton Hill Rd.	Confluence	Yes
T4.05	350 ft downstream of Carleton Hill Rd.	Roaring Brook confluence	Confluence	Yes
T4.06	Roaring Brook confluence	1/2 mile downstream of Moose Brook	Roaring Brook	No
T4.07	1/2 mile downstream of Moose Brook	1 mile downstream of Lake Gorielle	Moose Brook	No
<u>Upper Ammonoosuc River</u>				
T4.01	Connecticut River confluence	Weston Dam	Confluence	Yes
T4.02	Weston Dam	Upstream end of Red Dam impoundment	Expansion	No
T4.03	Upstream end of Red Dam impoundment	Nash Stream confluence	Expansion	Yes
T4.04	Nash Stream confluence	2000 ft downstream of Roaring Brook confluence	Nash Stream	Yes
T4.05	2000 ft downstream of Roaring Brook confluence	Covered bridge in Stark	Constriction	Yes
T4.06	Covered bridge in Stark	0.8 mi. upstream of Stark Covered Bridge	Expansion	No
T4.07	0.8 mi. upstream of Stark Covered Bridge	Downstream of railroad bridge in West Milan	Constriction	No
T4.08	Downstream of railroad bridge in West Milan	North Branch confluence	Expansion	No
T4.09	North Branch confluence	0.7 mi. downstream of Higgins Brook	North Branch	No

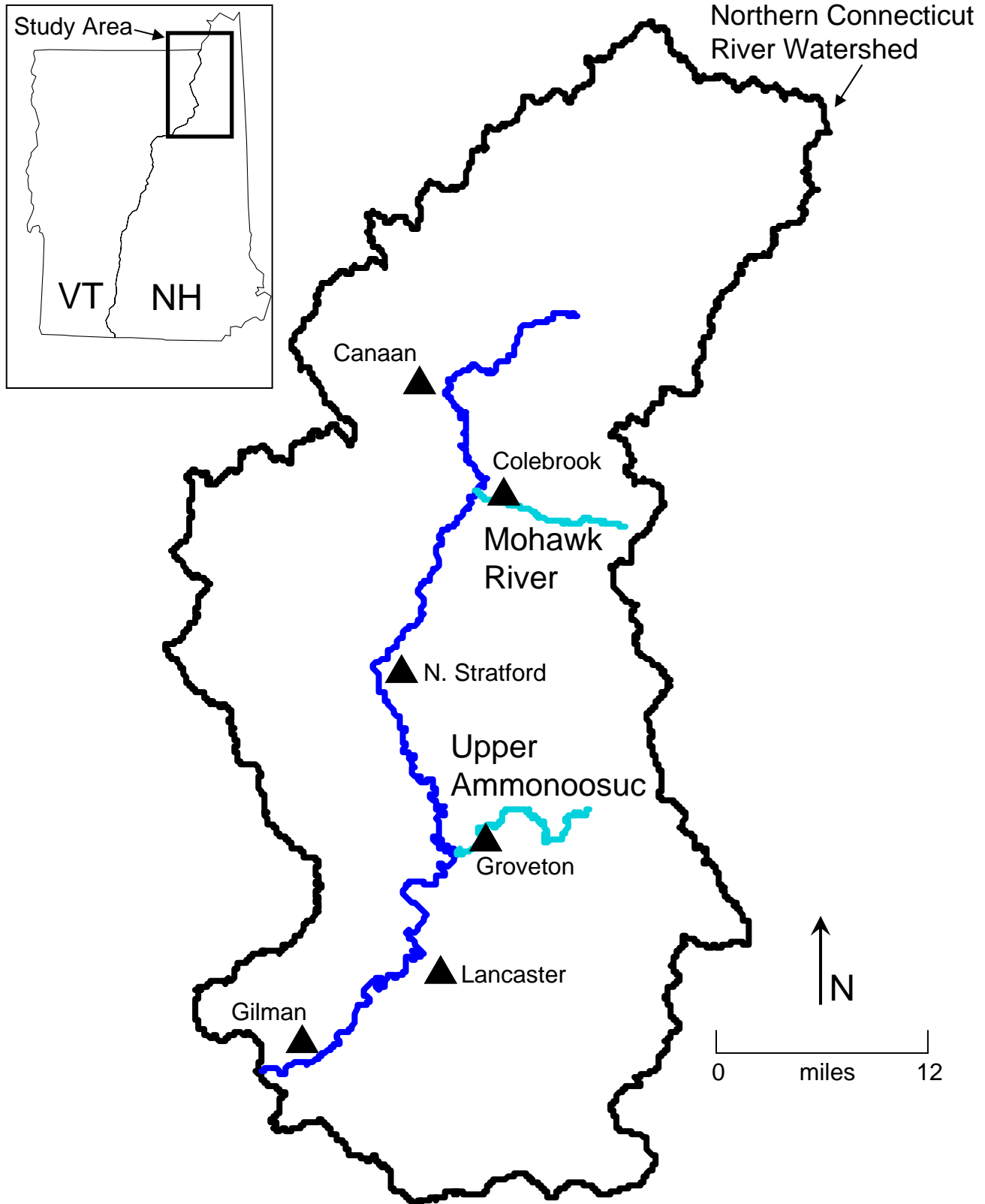
Fluvial Geomorphology Assessment of Northern Connecticut River Tributaries - Table 2

## Morphological Parameters of Reaches

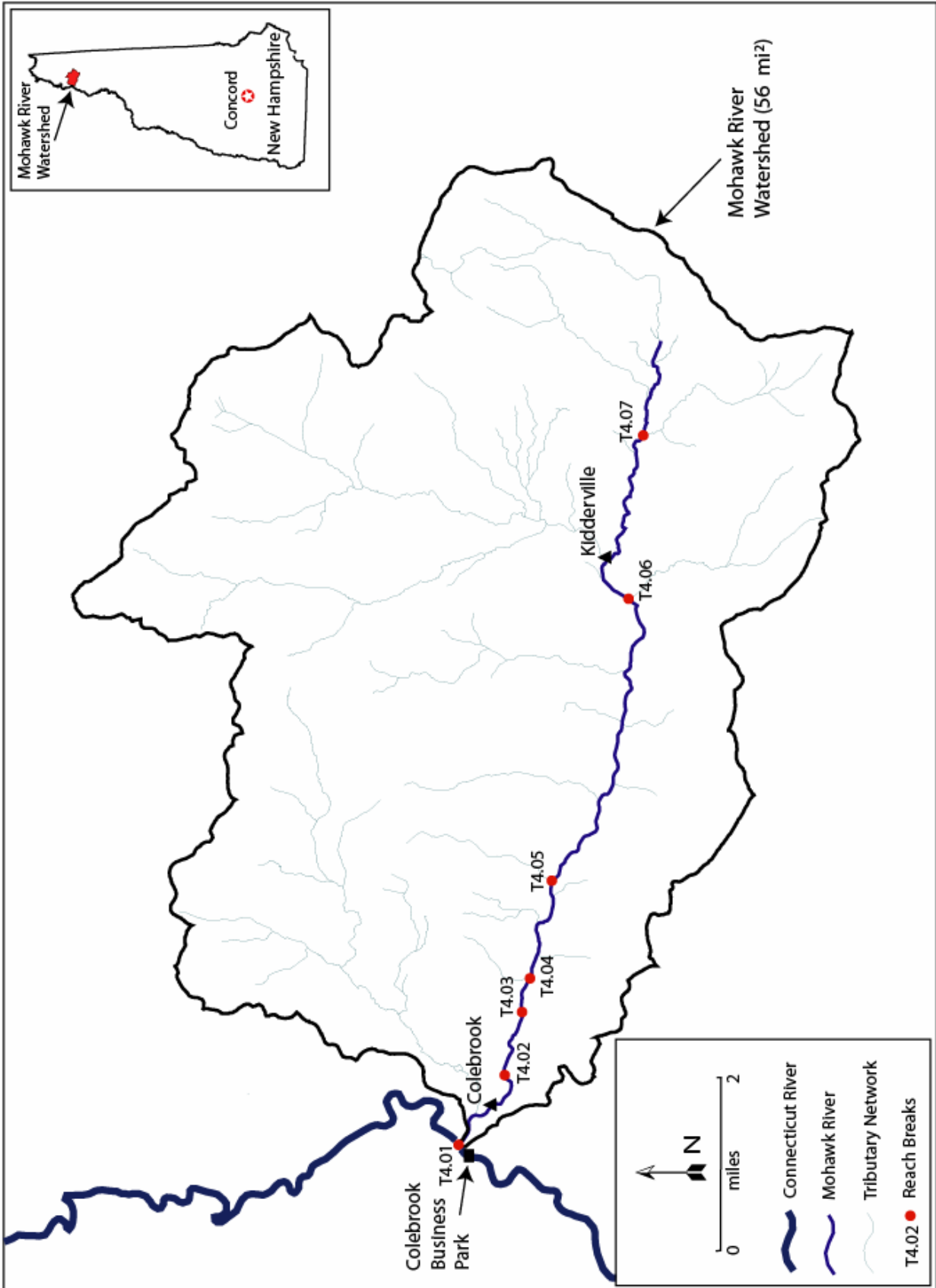
<u>Reach ID</u>	<u>Valley Confinement</u>	<u>Valley Width (ft)</u>	<u>Channel Gradient (%)</u>	<u>Sinuosity</u>	<u>Amount of Bar Development</u>	<u>Amount of Channel Migration</u>	<u>% Channelized</u>	<u>% Bank Erosion</u>
<u>Mohawk River</u>								
T4.01	Very Broad	2,397	0.49	1.22	High	Not Significant	57	16
T4.02	Broad	565	0.57	1.07	High	Low	67	22
T4.03	Broad	527	0.69	1.04	Not significant	Not Significant	100	5
T4.04	Broad	535	0.58	1.09	High	Low	36	12
T4.05	Broad	485	0.82	1.10	High	Not Significant	55	4
T4.06	Narrow	270	1.57	1.12	Low	Not Significant	49	11
T4.07	Narrow	142	3.89	1.05	Not significant	Not Significant	44	12
<u>Upper Ammonoosuc River</u>								
T2.01	Very Broad	12,648	0.08	1.93	High	High	23	12
T2.02	Broad	1,138	0.28	1.03	High	High	61	3
T2.03	Very Broad	1,867	0.26	1.04	High	Low	30	7
T2.04	Semi-confined	550	0.10	1.01	Not significant	Not Significant	0	4
T2.05	Very Broad	2,283	0.12	1.26	Low	Not Significant	65	8
T2.06	Semi-confined	403	0.20	1.05	Low	Not Significant	0	0
T2.07	Very Broad	1,347	0.03	1.79	Low	Low	18	7
T2.08	Broad	700	0.04	1.23	Not significant	Not Significant	31	12
T2.09	Very Broad	1,959	0.27	1.17	High	Low	75	NE*

\* Not evaluated

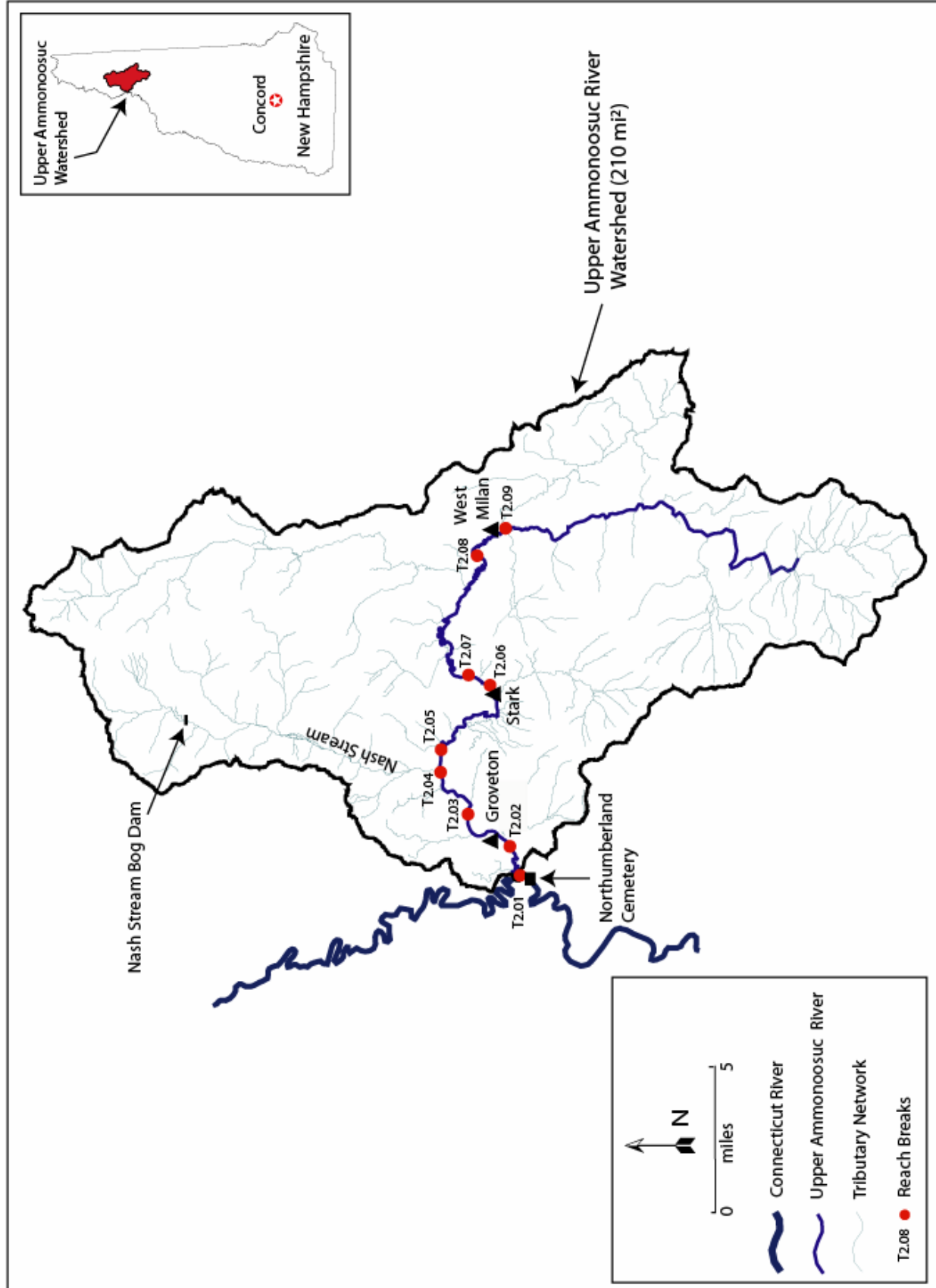
## Location of Connecticut River Tributaries



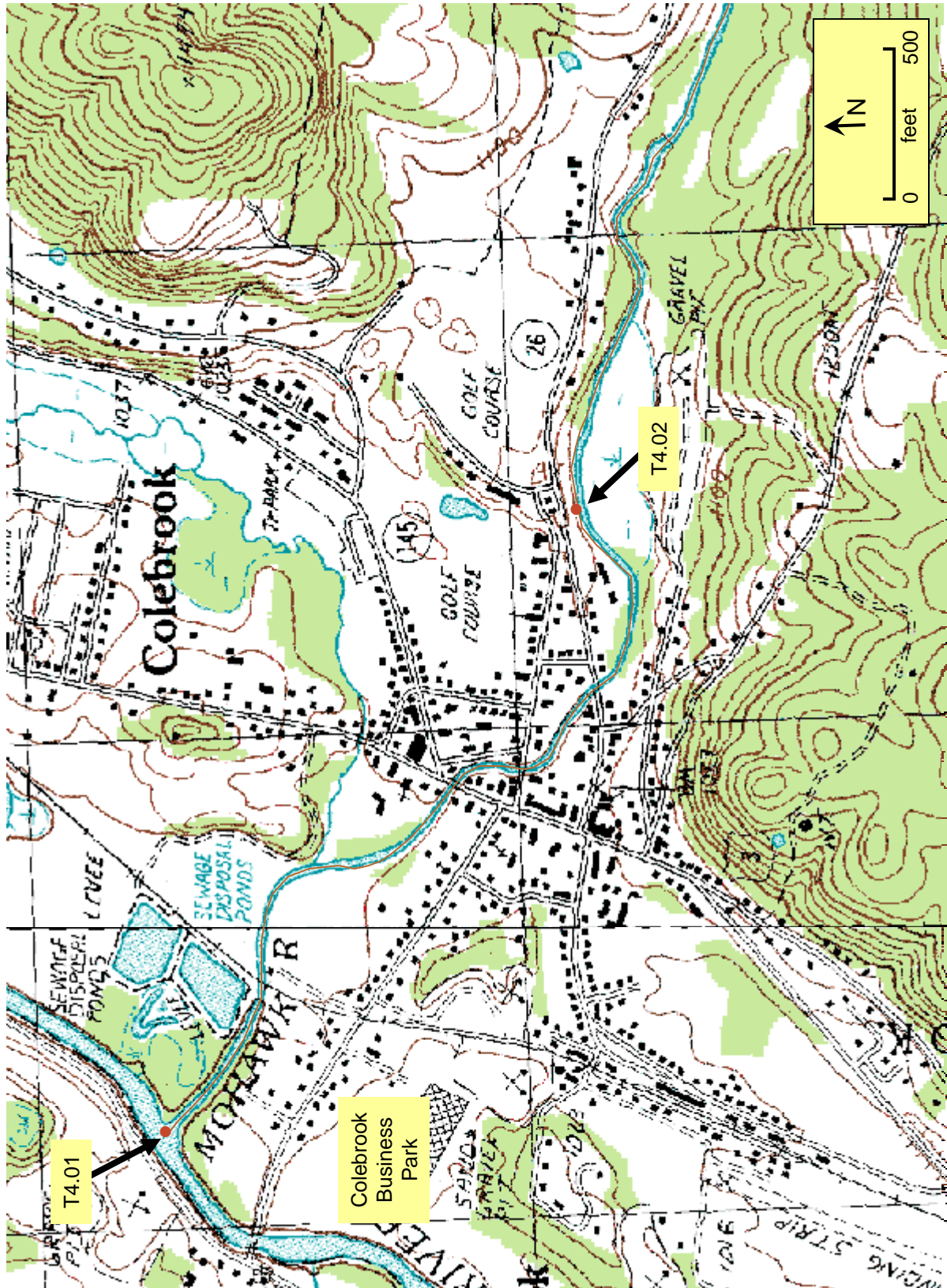
## Location of Mohawk River Reach Breaks



## Location of Upper Ammonoosuc River Reach Breaks

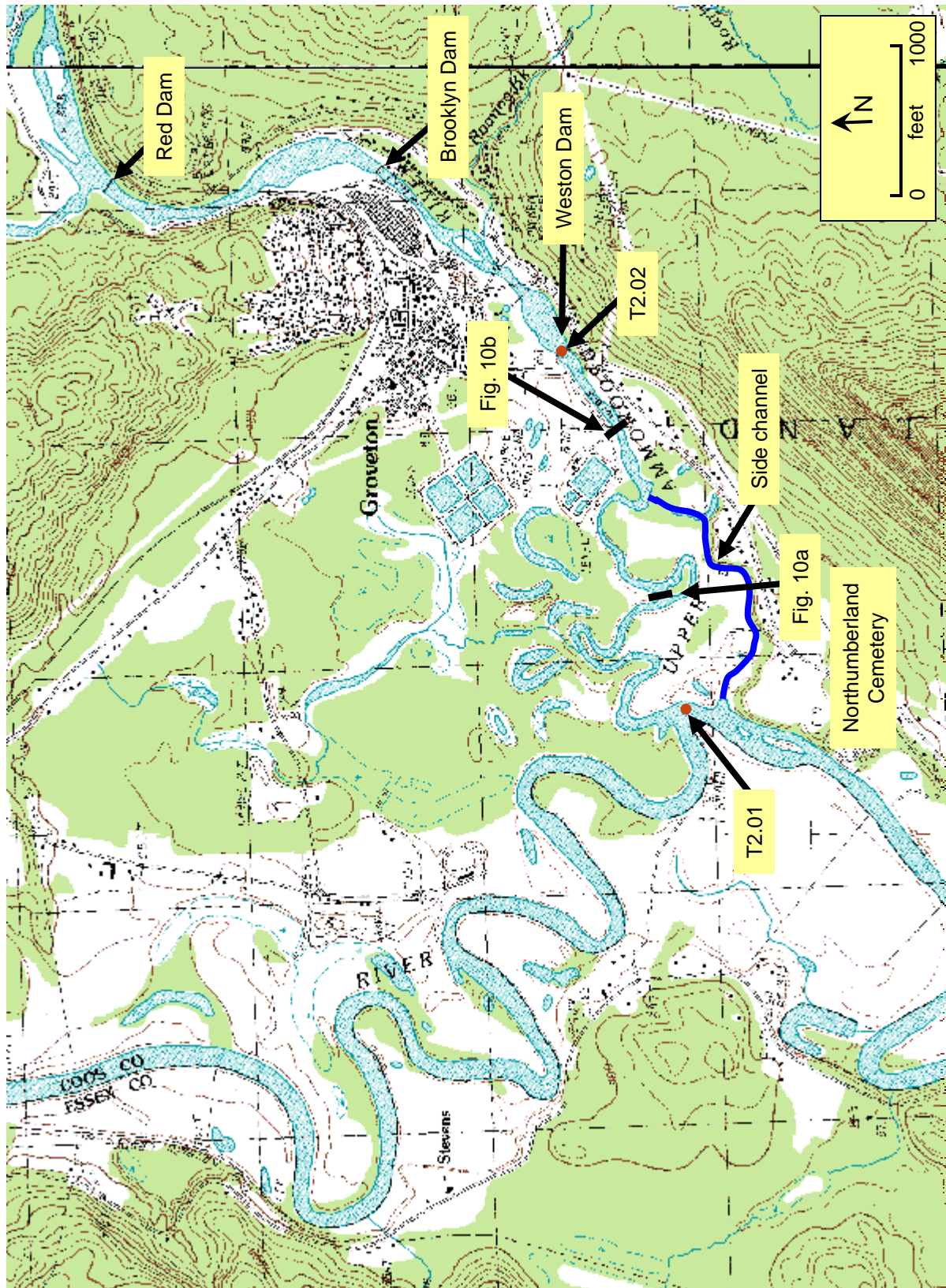


# Mohawk River Alluvial Fan (Reach T4.01)



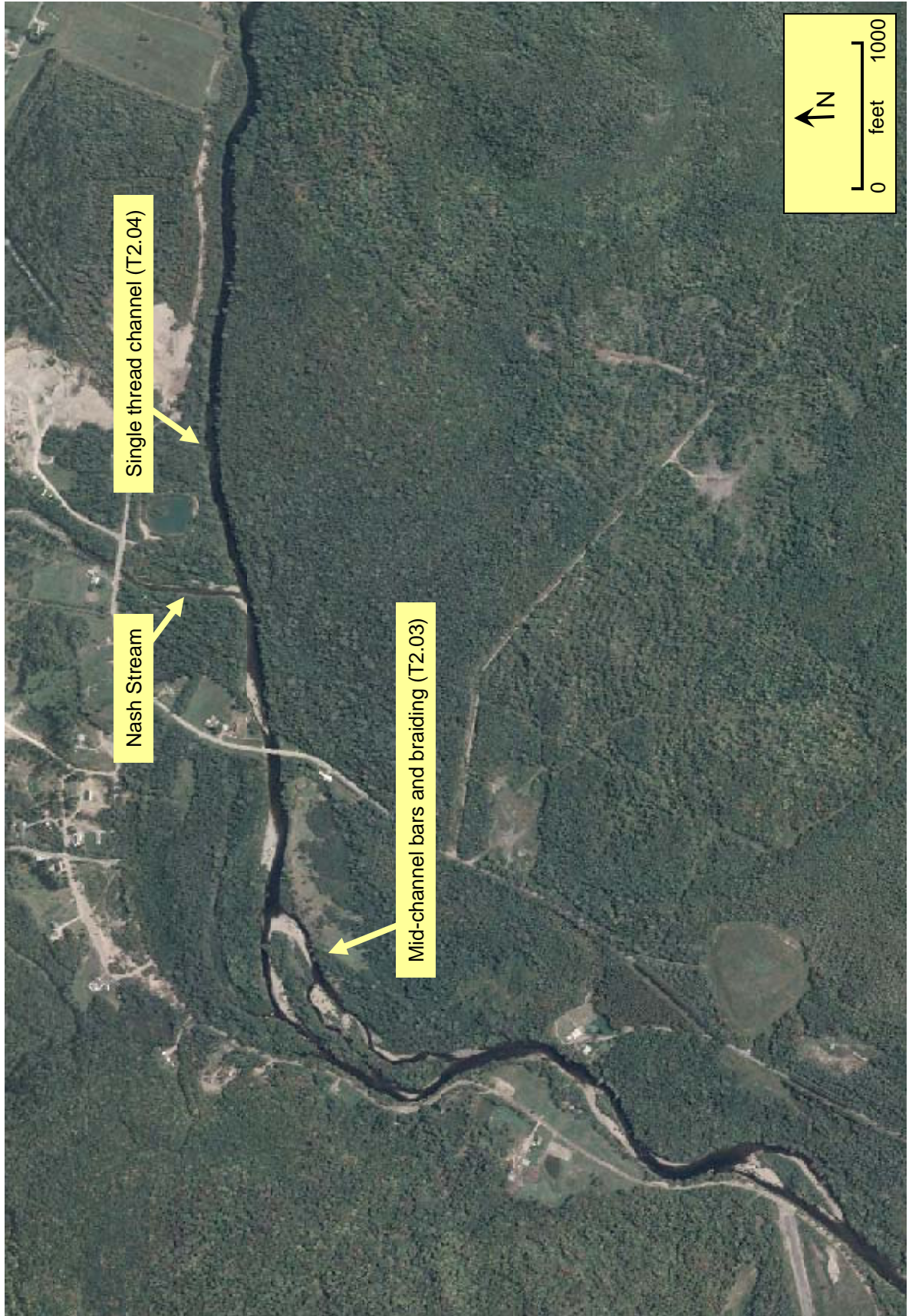


## Upper Ammonoosuc River Alluvial Fan (Reach T2.01)



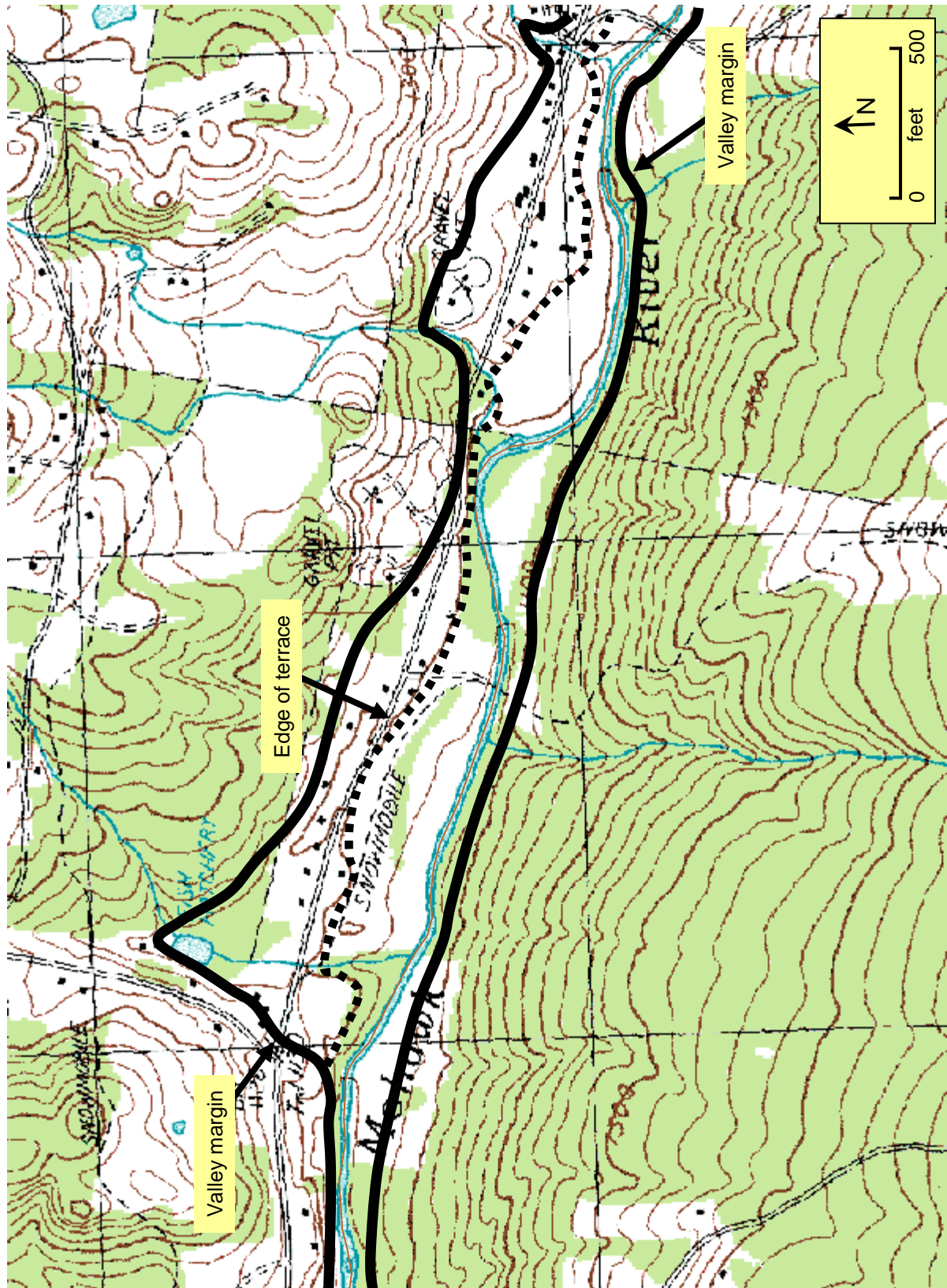


## Morphological Changes at the Nash Stream Confluence

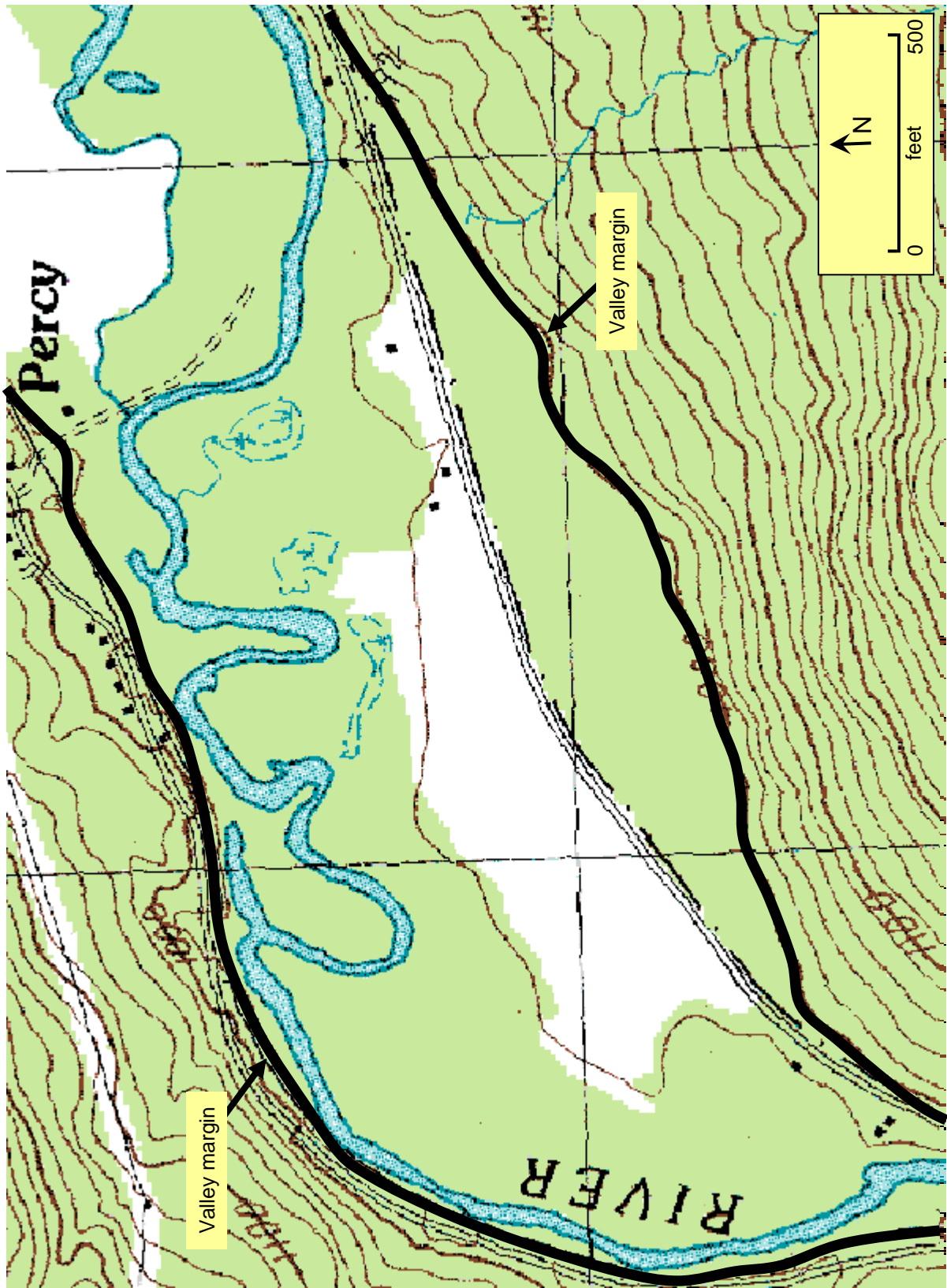




## Valley Confinement in the Mohawk River Valley (Reach T4.04)

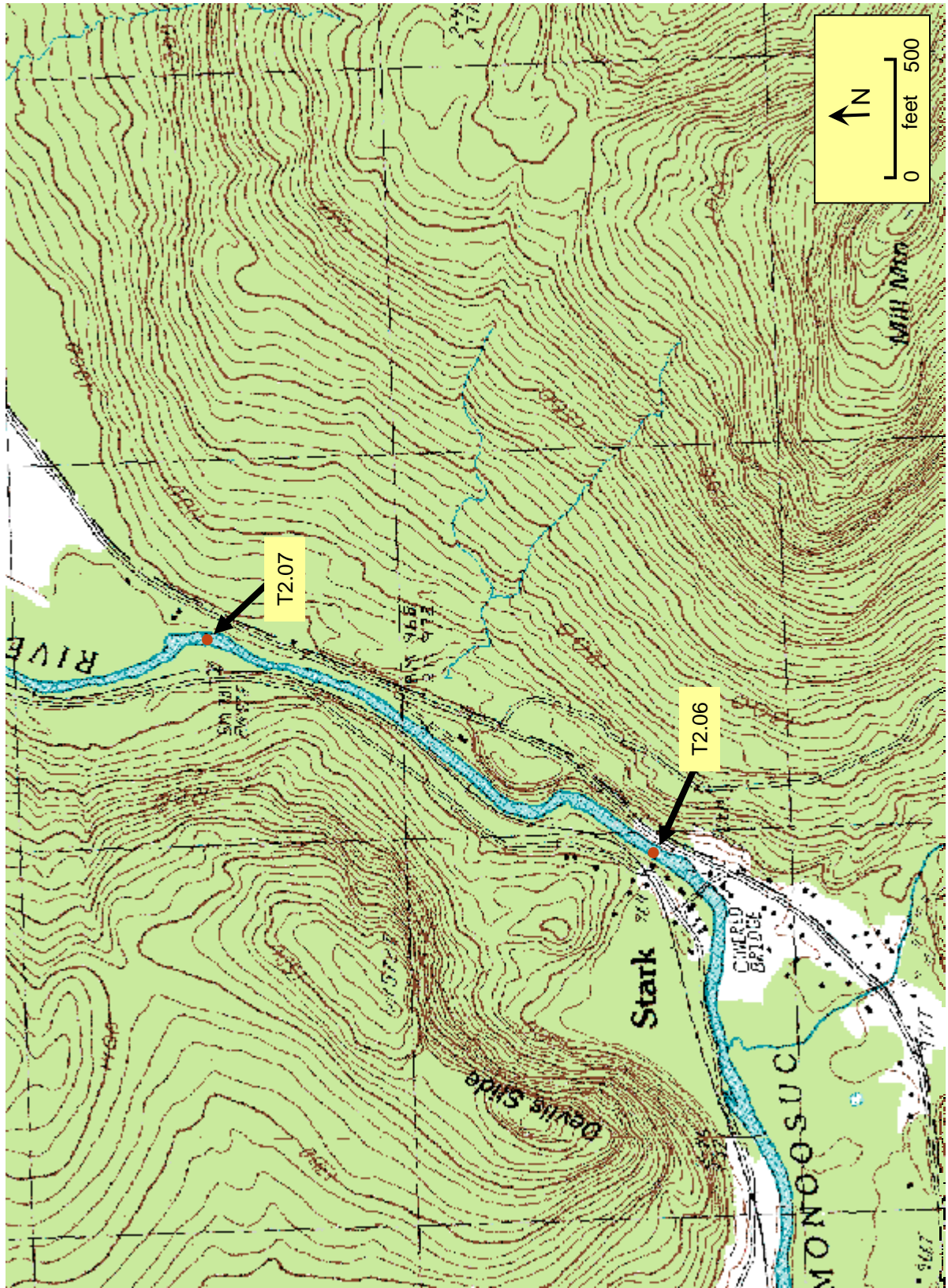


## Unconfined Valley on the Upper Ammonoosuc (Reach T2.07)

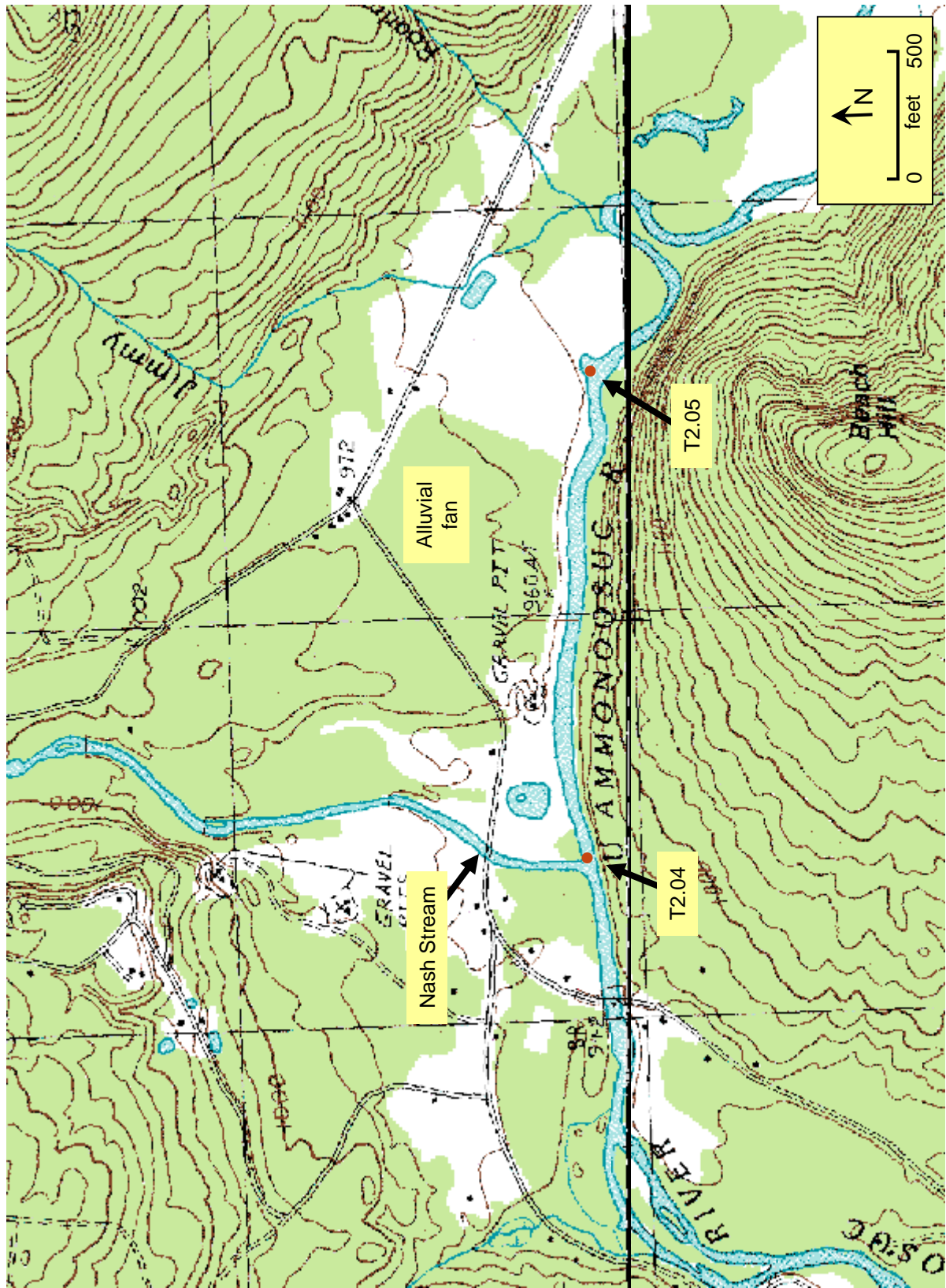




## Valley Confinement by Bedrock (Reach T4.06)

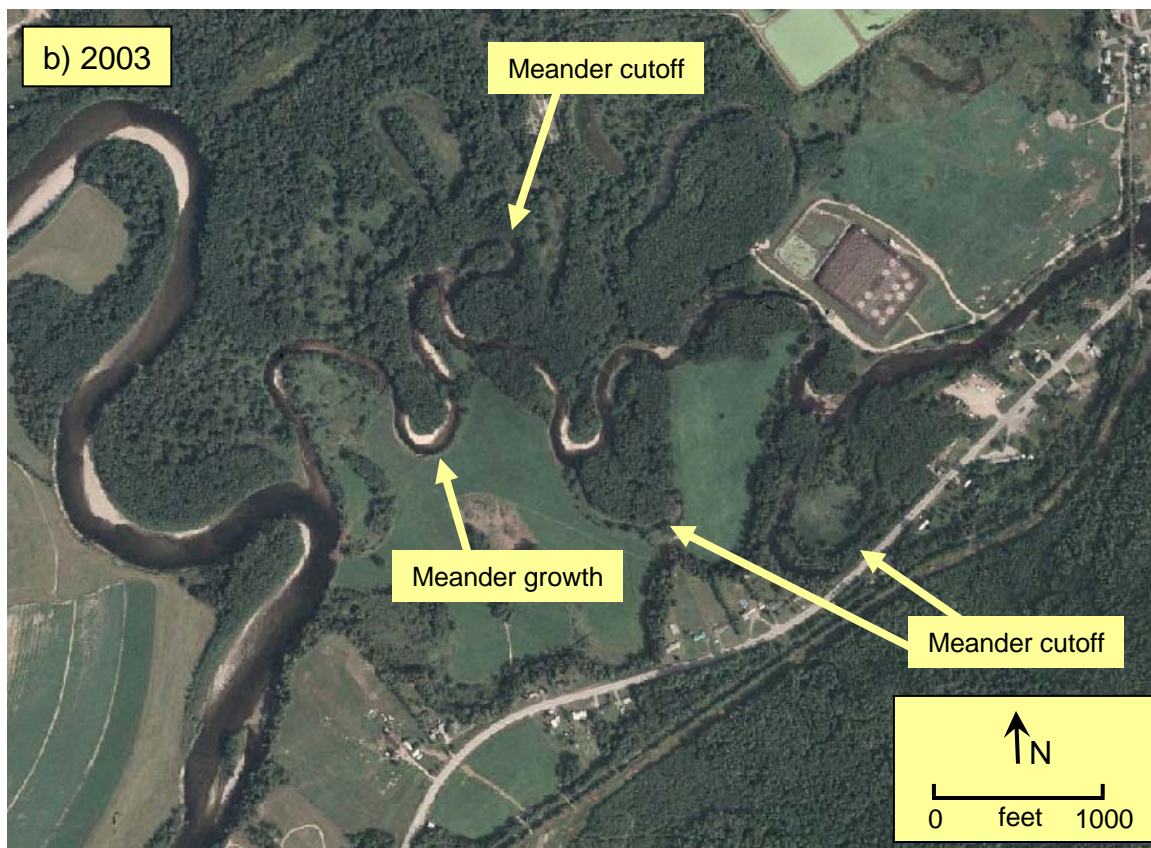
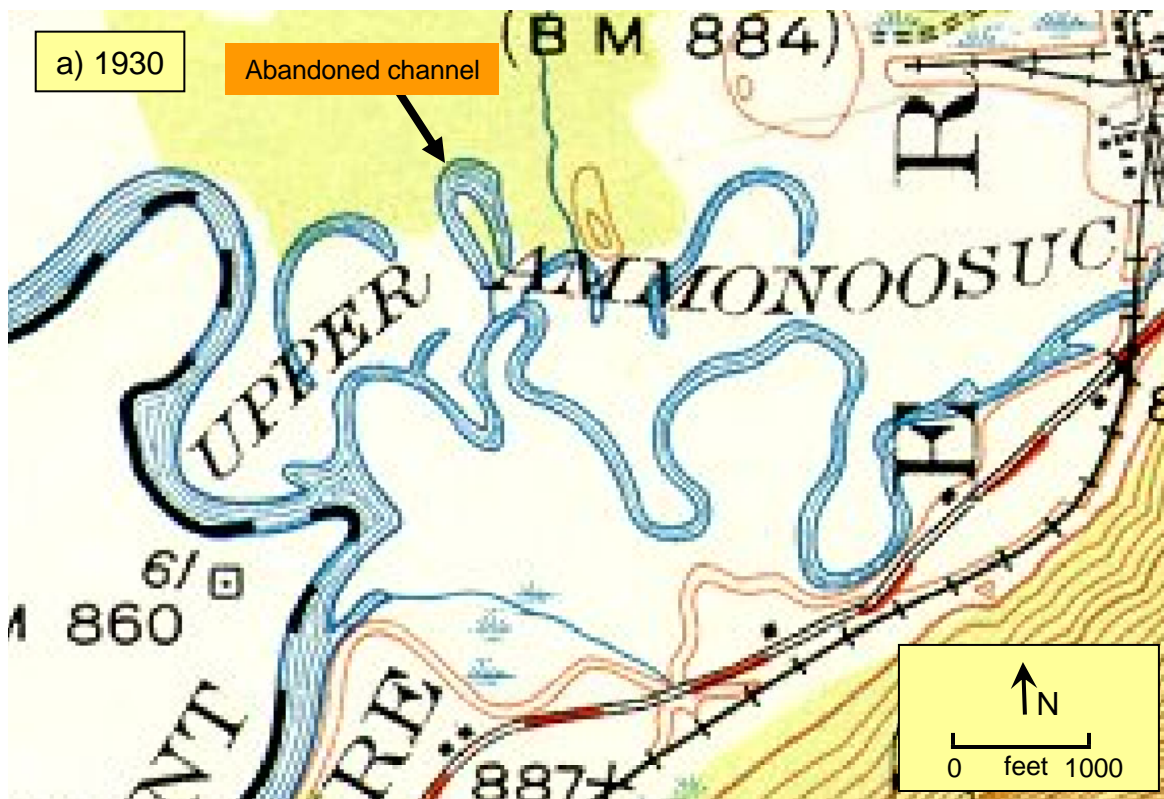


## Valley Confinement by Alluvial Fan Deposits (Reach T4.04)



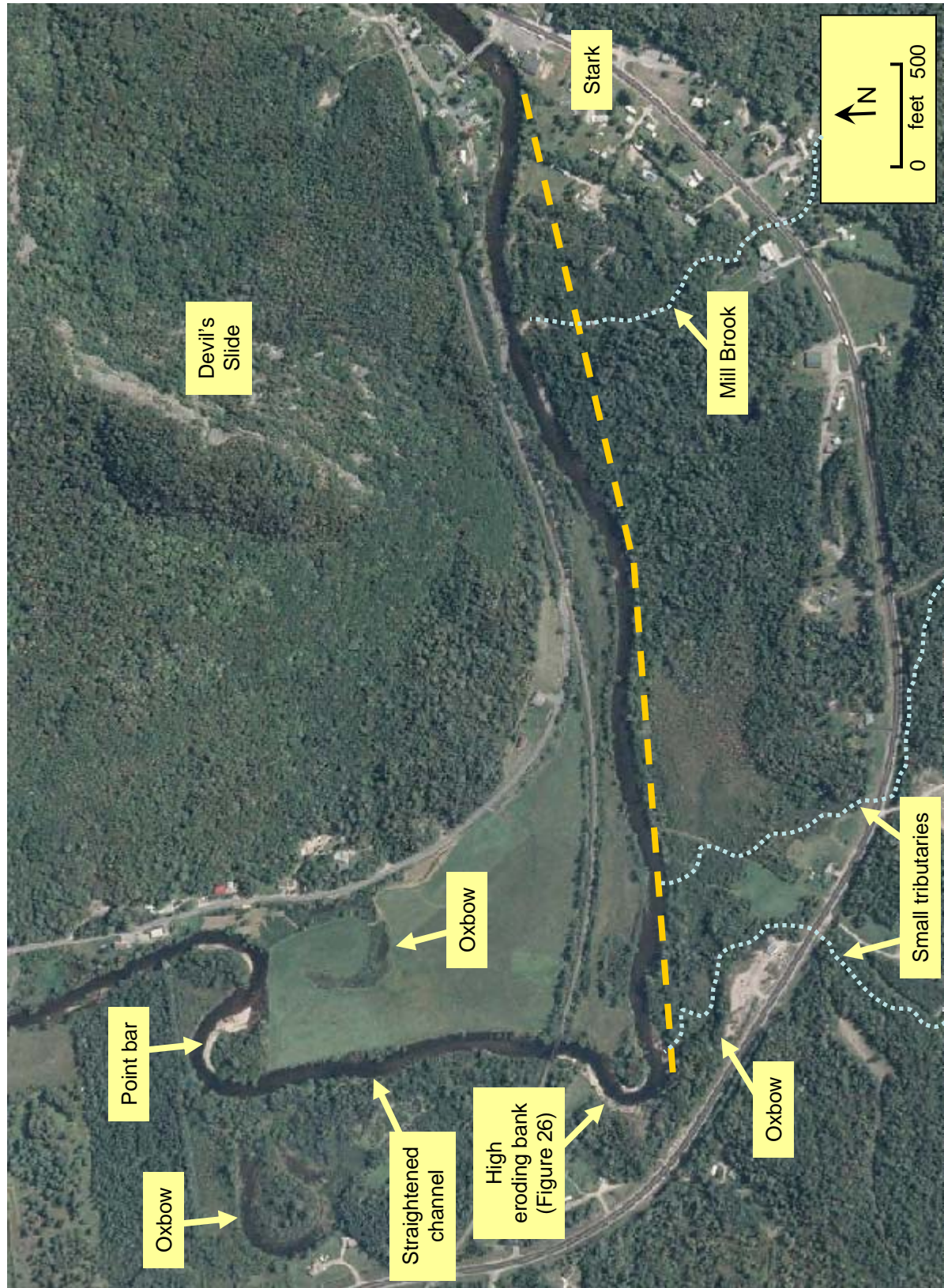


## Channel Changes on the Upper Ammonoosuc (Reach T2.01)





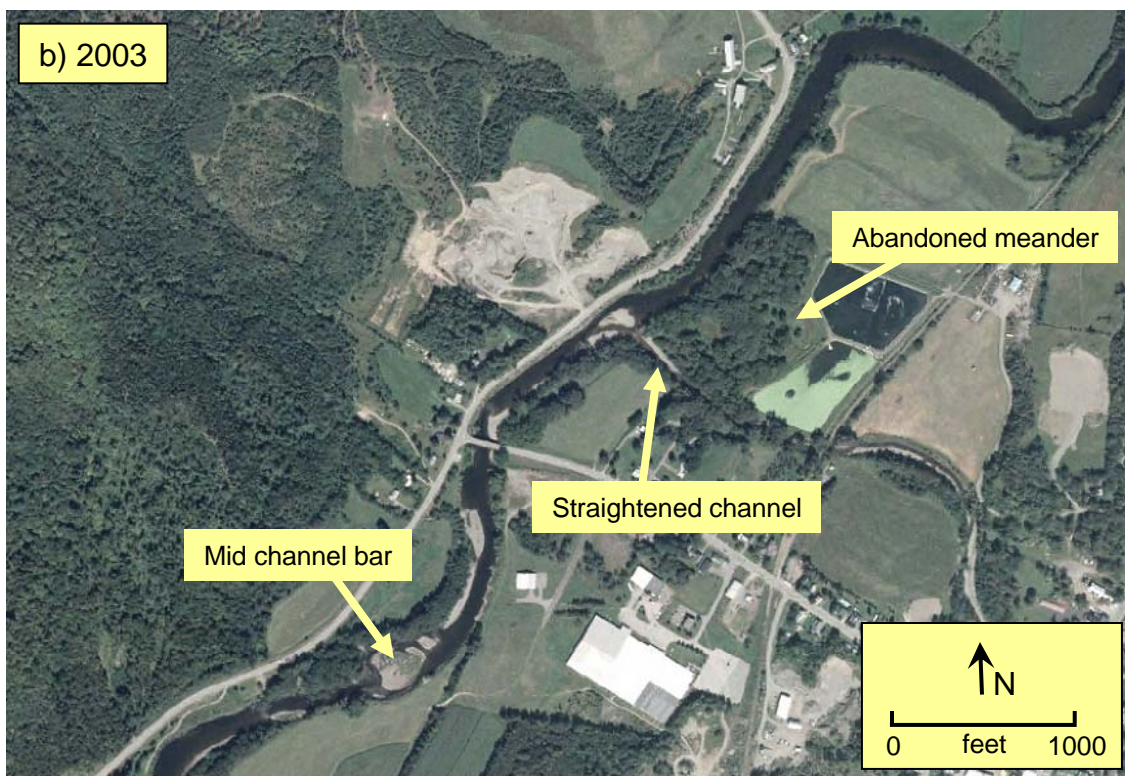
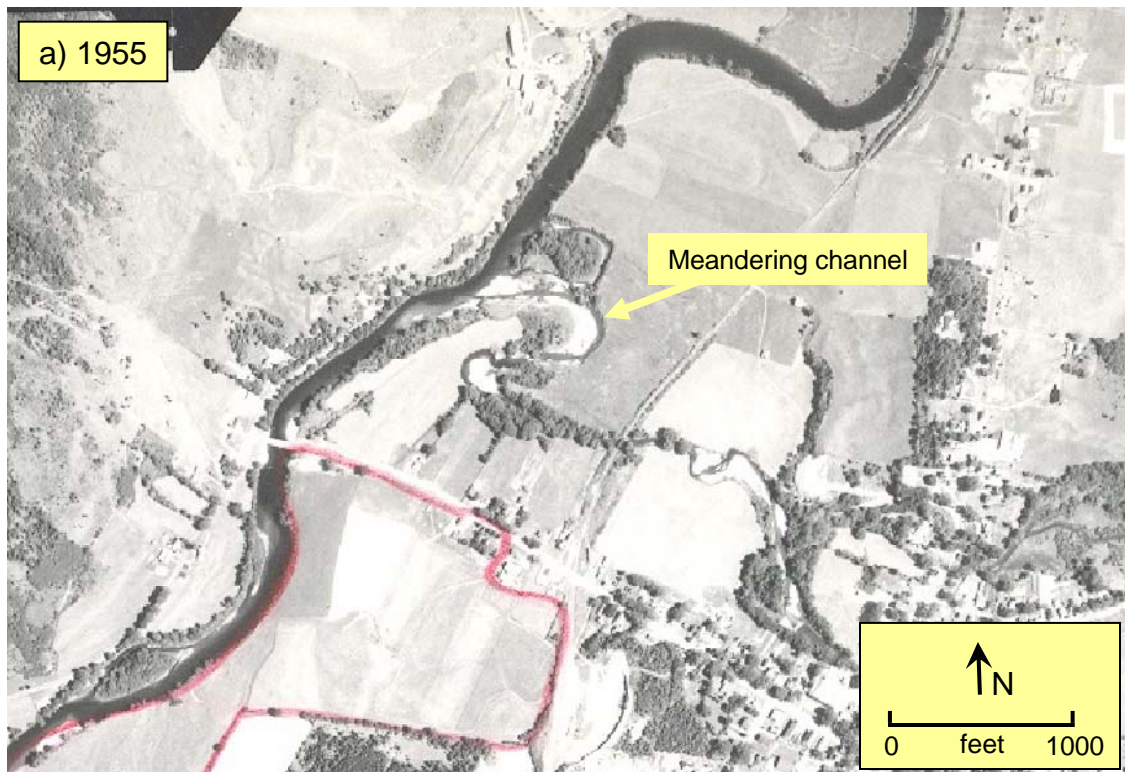
## Channel Straightening on the Upper Ammonoosuc (Reach T2.05)



Note: Dashed orange line represents original position of channel immediately after straightening

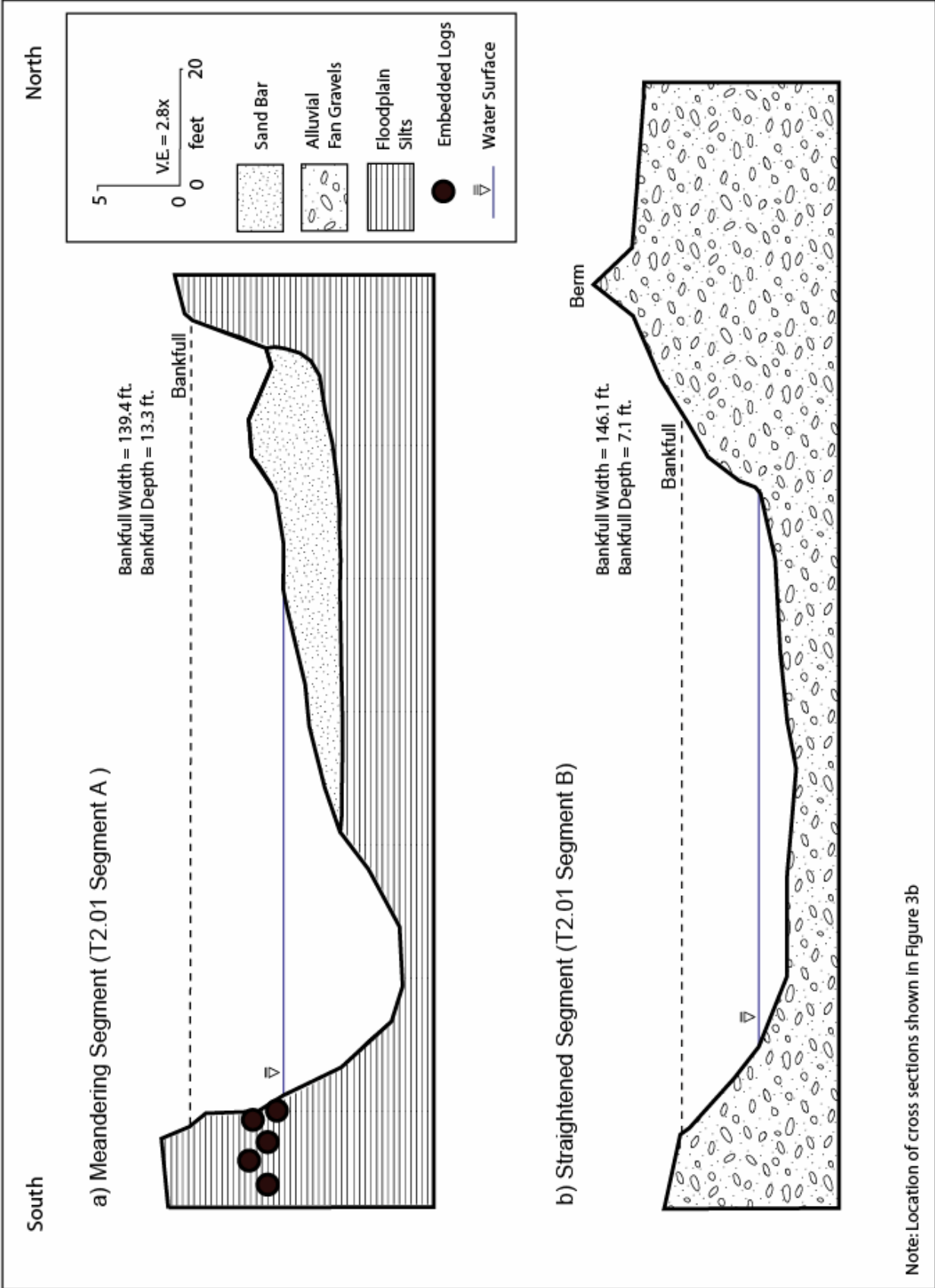


## Evidence for Channel Straightening in the 1960's on the lower Mohawk River (Reach T4.01)



Note: Channel position is unchanged between 1970 and 2003 aerial photographs

# Comparison of Upper Ammonoosuc Cross Sections





## Deltaic Deposits behind Red Dam (Reach T2.02)





## Erosion of Alluvial Fan Gravels (Reach T2.01)



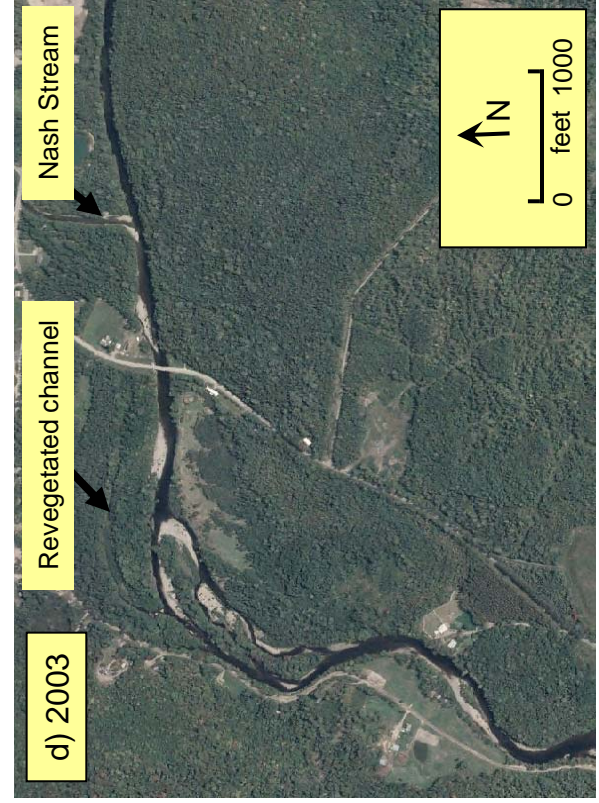
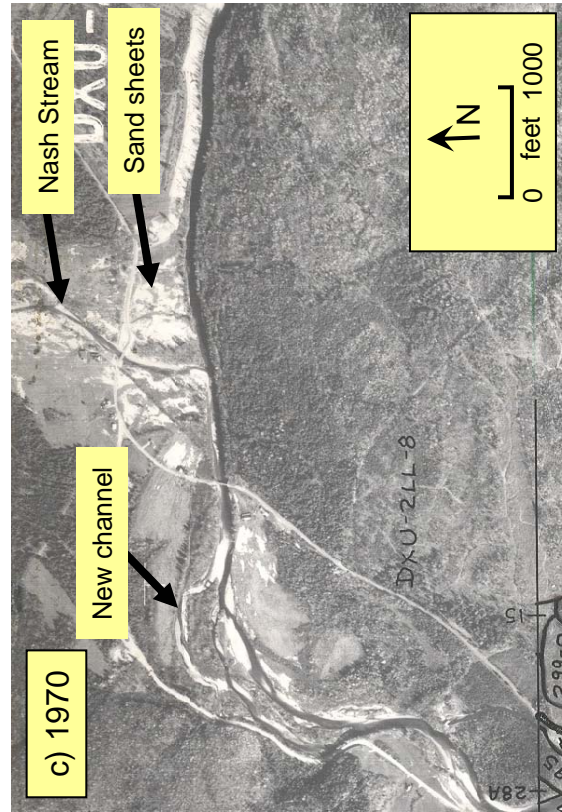
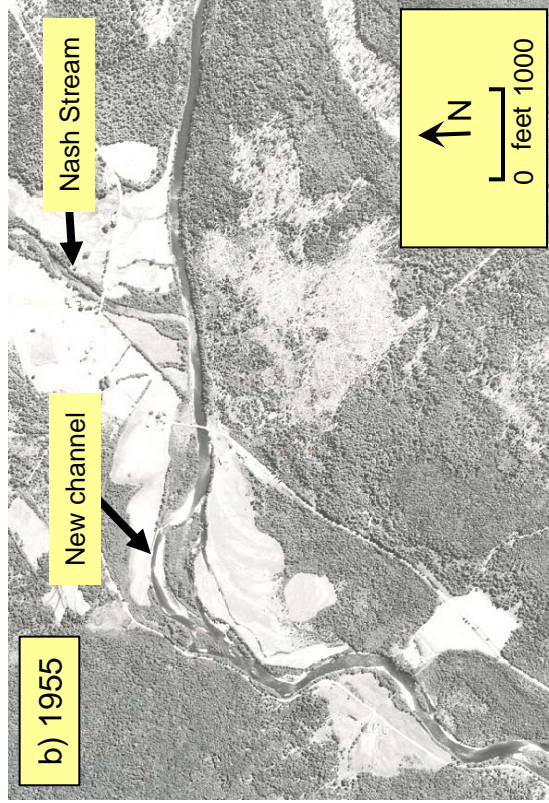
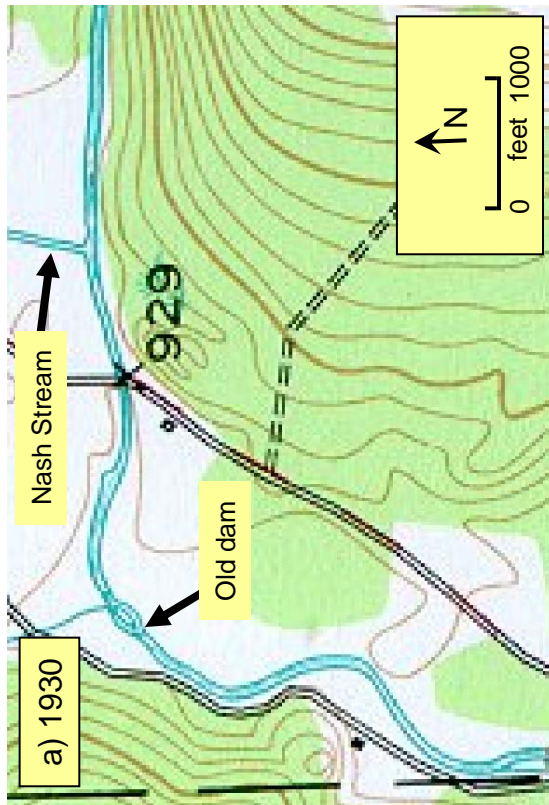


Sediment Accumulation behind the Breached Washburn Mill Dam (Reach T4.06)





# Channel Changes Downstream of Nash Stream (Reach T2.03)



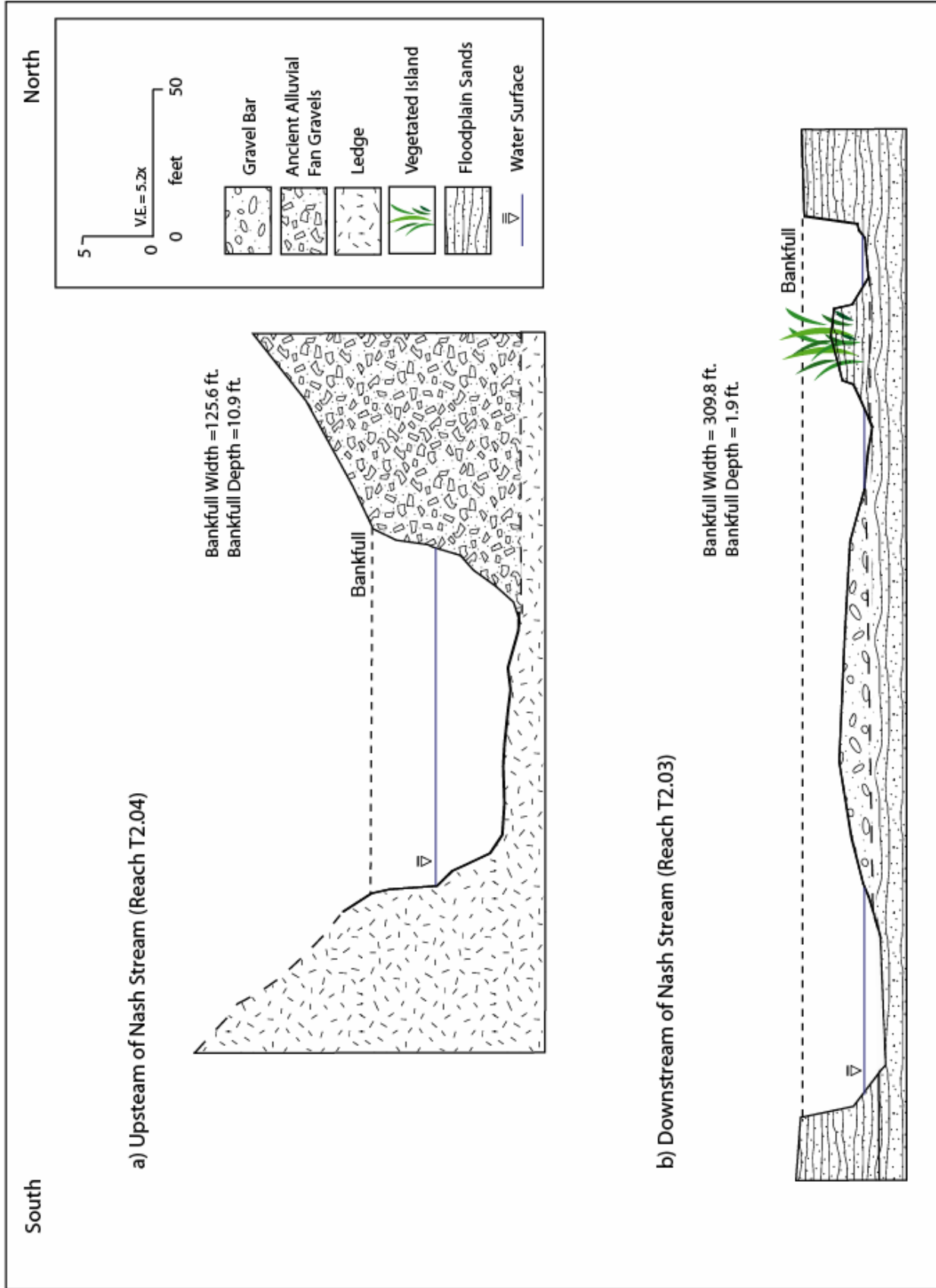
Note: New channel and revegetated channel are at same location in each photo



## Gravel Bar Downstream of Nash Stream (Reach T4.01)



# Comparison of Cross Sections Near Nash Stream





## Bank Armoring at the Mill Brook Confluence (Reach T2.05)



Note: View looking downstream on the Upper Ammonoosuc (Mill Brook out of view to the left)

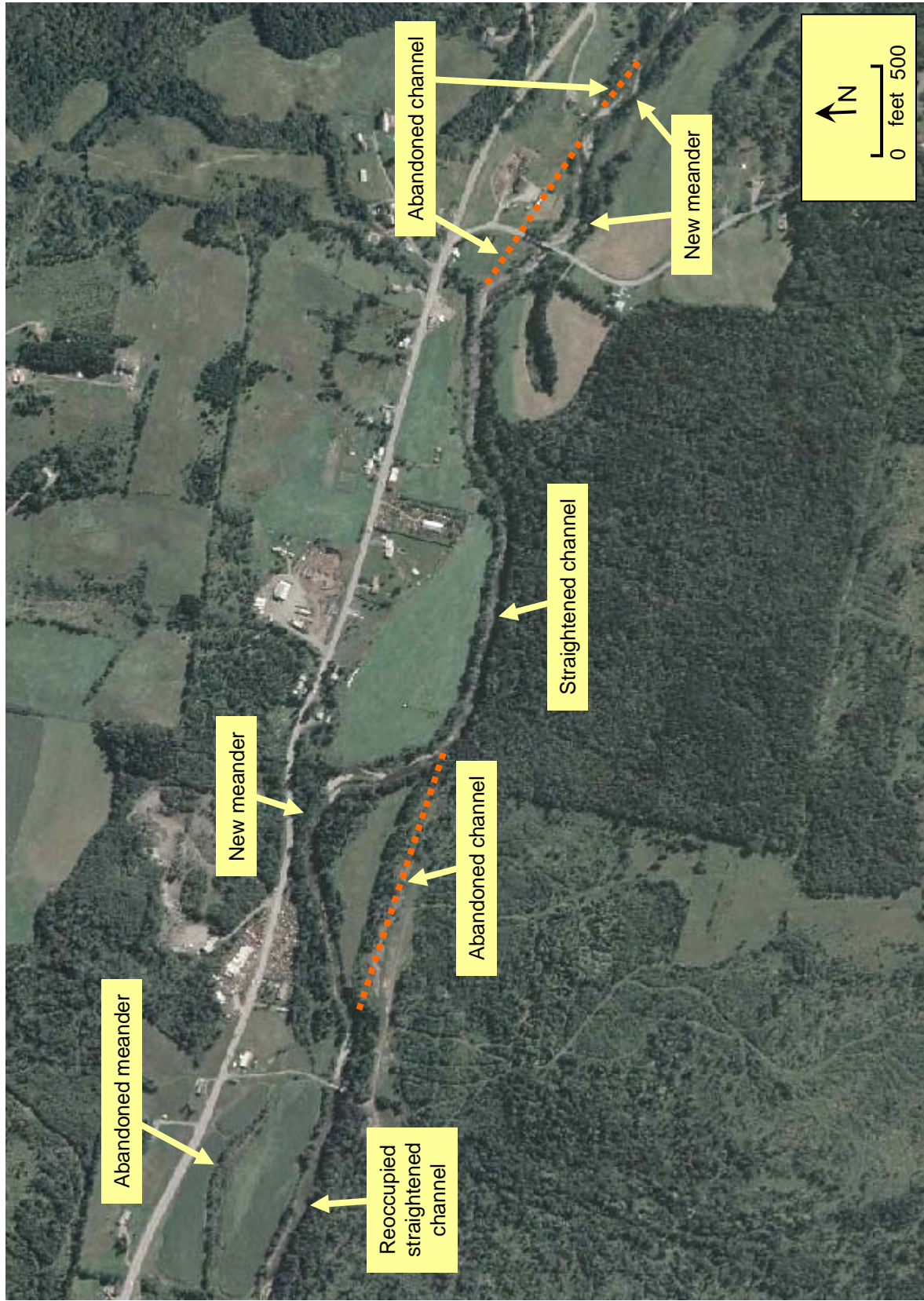


## Buried Logs on the Lower Upper Ammonoosuc (Reach T2.01)



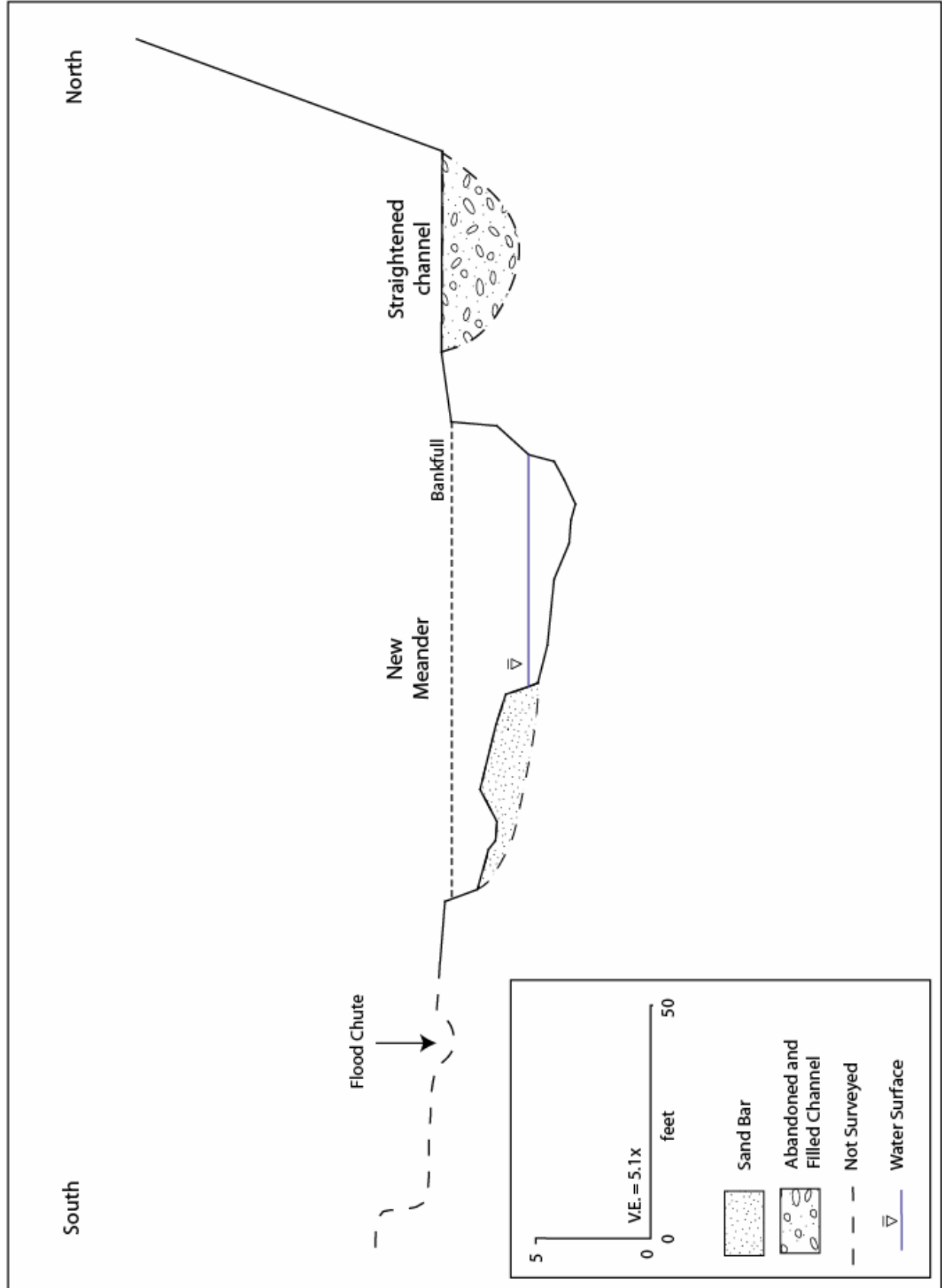


## New Meanders Formed at “Break Outs” on the Mohawk River



Note: Area shown is in Reach T4.04 and T4.05

## Cross Section of "Break Out" Area (Reach T4.05)





## Abandoned and Filled Straightened Channel (Reach T4.05)



Note: Photograph is taken in the middle abandoned channel of the three shown in Figure 19

## Erosion of High Bank on Mohawk River Caused by 1929 Flood



Note: Photo taken May 10, 1929 from the state highway (now Route 26) looking downstream



## Armored Eroding Bank Causing Downstream Deposition and Erosion (Reach T2.02)

a)



b)

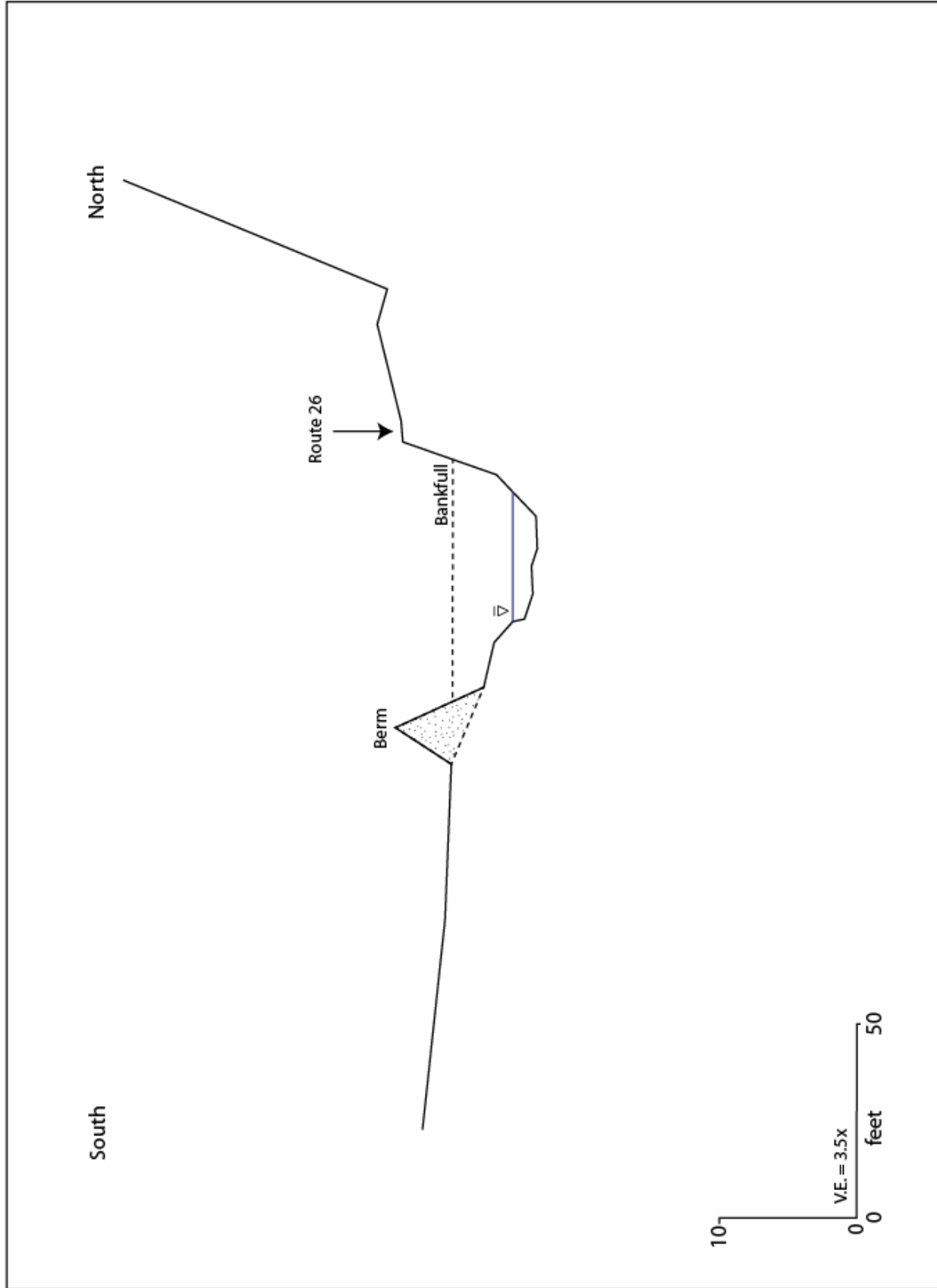




## Concrete Bank Armoring in Colebrook (Reach T4.01)

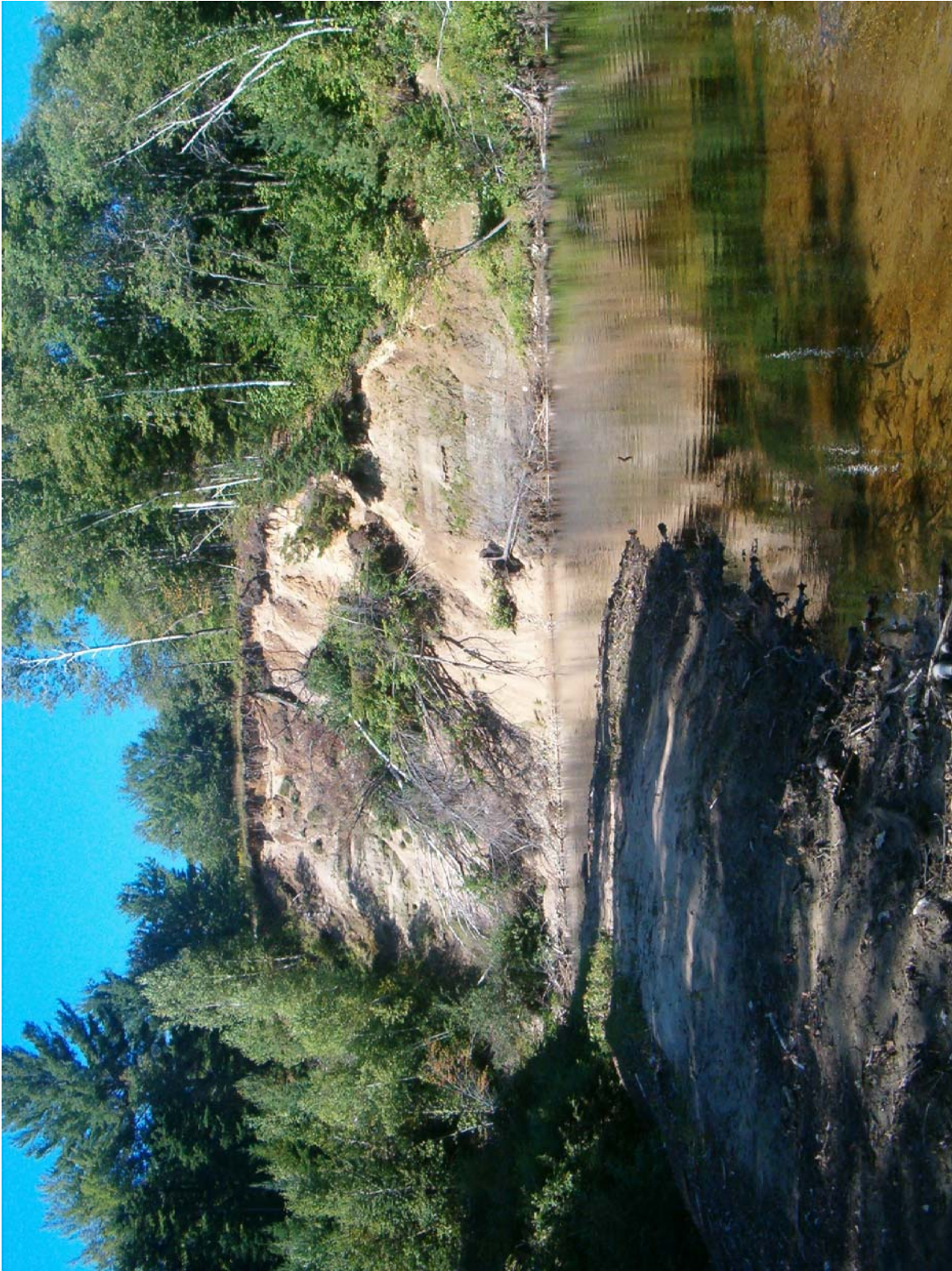


## Artificial Channel Confinements on the Mohawk River (Reach T4.06)





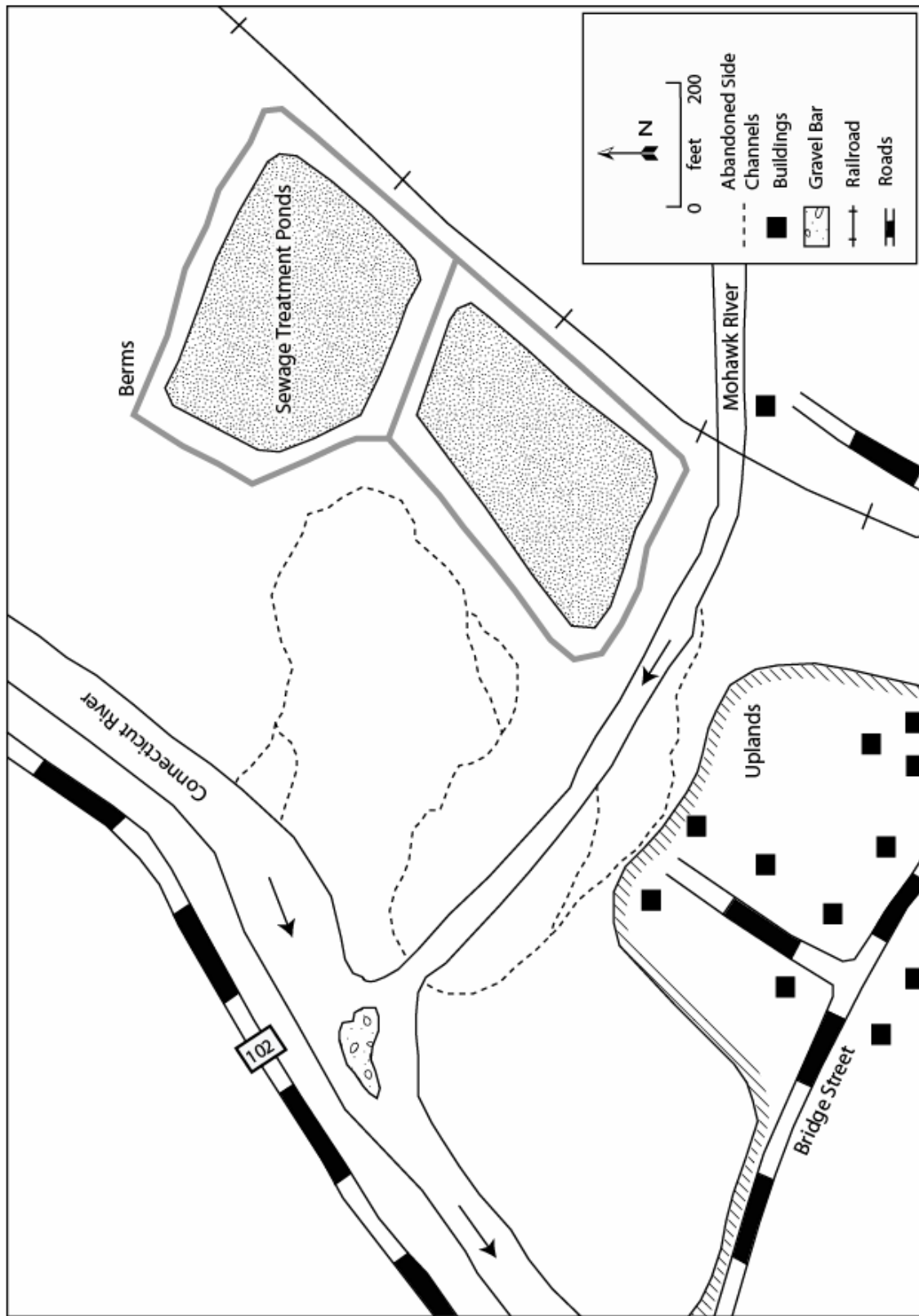
## High Eroding Bank of Glacial Outwash Deposits (Reach T2.05)



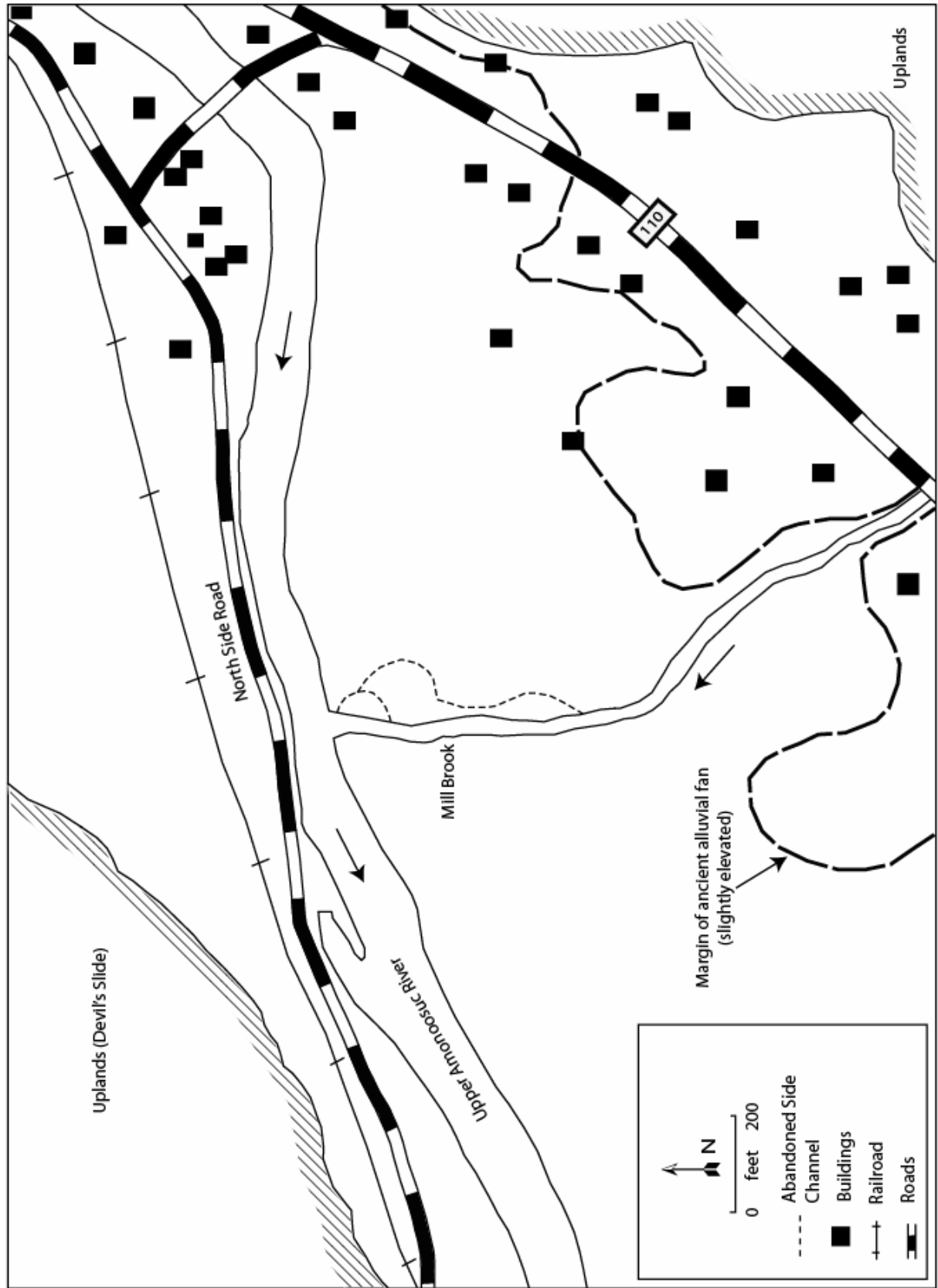
Note: Location of photograph shown in Figure 8. View looking upstream.



## Lower Mohawk River - Plan View



## Mill Brook Confluence - Plan View



Fluvial Geomorphology Assessment of Northern Connecticut River Tributaries - Figure 28